Preprints of the 21st IFAC World Congress (Virtual)
Berlin, Germany, July 12-17, 2020

Repetitive Control of Neutral-Point Voltage in NPC Three-Level Inverters Based on EID Compensation ⋆

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Abstract: Neutral-Point clamped (NPC) three-level inverters have a broad application prospect. However, the voltage imbalance of the capacitors and the drafting of its neutral-point voltage will generate voltage stresses on the switches and even increase the total harmonic distortion (THD) rate in their output. In this paper, an improved repetitive control method based on the idea of equivalent input disturbance (EID) compensation is adopted. By adding an additional neutral-point branch, the neutral-point voltage control problem is transformed into a disturbance suppression problem. The case studied are tested using MATLAB/SIMULINK software and the experiment results show that this proposed control strategy can overcome both periodic and non-periodic disturbance, restraining the voltage fluctuation at the neutral point to a lower level.

Keywords: Total harmonic distortion rate, three-level inverter, repetitive control, equivalent input disturbance, neutral-point voltage control.

1. INTRODUCTION

Compared with the traditional two-level converters, multi-level converter topology has many advantages in improving system output performance, saving energy and reducing consumption, reducing system volume and cost. Therefore, the application of multilevel inverters in high-voltage and high-power systems has a broad prospect. One of the most commonly used multilevel converters is the neutral-point clamped (NPC) three-level topology, which has the characteristics of high voltage capacity and low harmonic output (Wang et al. (2019) and Subsingha and Amarnpitakwattana (2018)). Although the three-level NPC topology has obvious advantages over the traditional two-level topology in high-power applications, it still has some inherent problems, such as voltage drift and voltage fluctuation at the neutral point, which is caused by excessive neutral-point current during the transition or for an unbalanced load. Specically, there is a low frequency voltage disturbance in the neutral-point potential of the circuit, and the voltage fluctuation between the capacitors contains an error signal of three times the frequency of the circuit subgrade wave. Therefore, when the NPC three-level inverters work, the potential imbalance at the neutral point will have a certain impact on the output quality of the system, and then affect its practical application (Ja-Hwi Cho et al. (2013), Mounira et al. (2018)).

⋆ This work was supported in part by the National Natural Science Foundation of China under Grant 61973318.

The fluctuation of neutral-point potential can be divided into neutral-point voltage pulsation and neutral-point voltage drift. The fundamental causes of voltage pulsation at neutral point are topology and control methods (Liang et al. (2015)). The reasons for the neutral-point voltage drift include the difference of dc side capacitance parameters, the difference of switching device characteristics and the asymmetry of load.

There are mainly two strategies to realize the neutral-point voltage control of NPC three-level inverters. One is based on hardware circuits such as replacing the bus-capacity with two dc sources or adding a balancing circuit on the dc side, which would increase the cost and the complexity of the system (Zhang et al. (2012)). In addition, the output of the power source itself is unstable or susceptible to external conditions, making it difficult to apply to the renewable energy power generation system. The other way is based on software algorithms, being mainly to add the suppression algorithm of neutral-point potential fluctuation in pulse width modulation (PWM) control strategy by software, instead of adding extra hardware circuit, so it is the popular suppression method of neutral-point potential fluctuation at present. The authors of Lawan et al. (2019) and Lin et al. (2019) studies a SVPWM method based on space vector, this method can effectively suppress the voltage fluctuation at the neutral point caused by modulation strategy, but cannot solve the fluctuation caused by circuit parameters and load asymmetry, and will increase the number of synthetic vectors, leading to the switching

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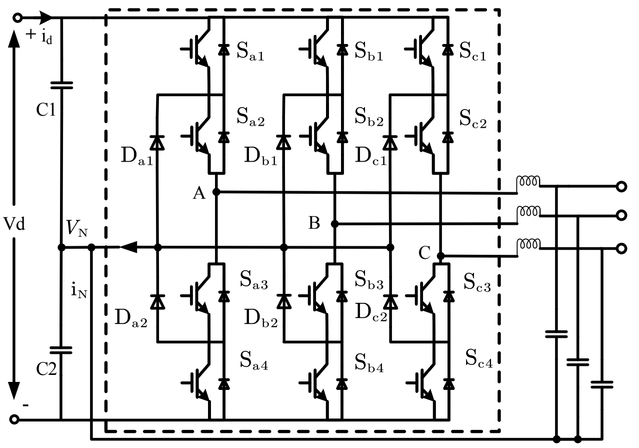


Fig. 1. Diode-clamped three-level inverter circuit

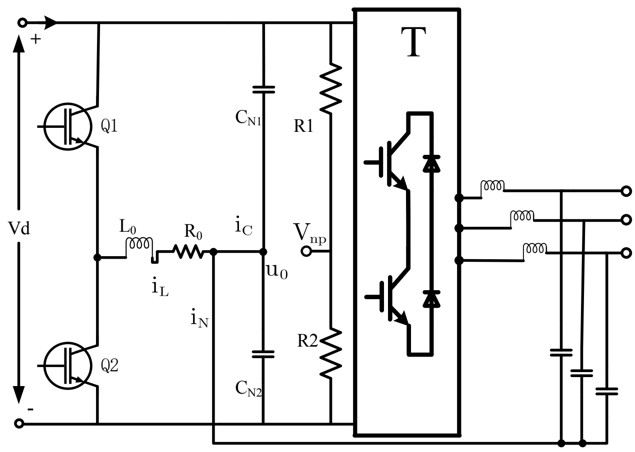


Fig. 2. Equivalent model

loss. The authors of Lyu et al. (2015), Bahrami and Narimani (2019) proposed a SPWM method based on carrier, which can suppress the voltage fluctuation at the neutral point by superimposing zero sequence components on the modulated wave. However, the selection of zero sequence components requires a high degree of skill.

To deal with this problem, a repetitive control system can be used to reject periodic neutral-point voltage pulsation (Yan et al. (2019)). However, repetitive control method cannot reject the voltage drift at the neutral point, which has irregular frequency components. In this paper, an improved repetitive control method based on equivalent input disturbance (EID) was designed to overcome the neutral-point voltage deviation (Wu et al. (2011)). It is proposed here that repetitive control eliminates periodic interference in neutral-point voltage, and EID is applied to compensate the defects of repetitive control and eliminate the remaining neutral-point voltage drift. Firstly, based on analyzing the mathematical model of NPC three-level inverter, the equivalent neutral-point voltage control system model is established. Then, the structures of the repetitive control and an repetitive control based on EID are proposed respectively. Finally, the validity and superiority of the proposed method are tested using MATLAB/SIMULATION software.

2. PROCEDURE FOR PAPER SUBMISSION

2.1 System Description

Figure 1 shows the structure of the diode hoop type threelevel inverters. The topology consists of three bridge arms, each of which has two hoop diodes, four power diodes and four relay diodes. Capacitors $C1$ and $C2$ have the same size, so the voltage on each capacitor is $Vd/2$. The midpoint of the two series devices is connected with the neutral point of the dc side capacitor through the hoop diode, so that the output voltage of the hoop position is at the neutralpoint potential of the dc side, that is, the voltage on each switch device is limited to one $Vd/2$.

The model being studied is given in Fig. 2. Extra IGBTs, $Q1$ and $Q2$, are added to the circuit and the controllers task is to generate emission pulses for the two switches. The average output voltage in a period can be tuned by adjusting the duty cycle of PWM, the control objective is to make the voltage at the midpoint of the capacitors, u_0 , very close to the true neutral-point voltage, V_{np}, by controlling the IGBTs, $Q1$ and $Q2$. V_d is the voltage of the DC source. It is worth noting that V_{np} is measured at the neutral point of the two resistors $R1$ and $R2$, and $R1 = R2$.

Module T is used to represent the circuit structure composed of A, B and C phase point stirrup bridge arm in Fig. 1, and then the equivalent neutral-point voltage control model as shown in Fig. 2 is established, it is a slight adjustment to the model of Zhong et al. (2006).

2.2 Mathematical Model

All voltages are measured with respect to the reference point voltage, u_0. Letting the voltages of the capacitors are $V_{C_{N1}}$ and $V_{C_{N2}}$, respectively. then the relationship between the total dc-link voltage, V_d, and the two capacitor voltages, $V_{C_{N1}}$ and $V_{C_{N2}}$, is

$$V_d = V_{C_{N1}} - V_{C_{N2}}. \tag{1}$$

The desired neutral-point voltage, $u_0 = V_{np}$, is the average voltage of the capacitors, then

$$V_{np} = \frac{(V_{C_{N1}} + V_{C_{N2}})}{2} \tag{2}$$

We obtain the following equations according to Kirchhoffs laws:

$$u_N = L_0 \frac{di_L}{dt} + Ri_L, i_N = i_C + i_L \tag{3}$$

Where u_N is the voltage of the induct L_0 and resistor R_0, and

$$i_C = C_{N1} \frac{dV_1}{dt} + C_{N2} \frac{dV_2}{dt} \tag{4}$$

and the relationship between u_N and the control input u is:

$$u = u_N - V_{np} \tag{5}$$

Through some simple mathematical treatment of the above equations, the following results can be obtained:

$$\begin{cases} \dfrac{di_{L_0}}{dt} = -\dfrac{R}{L} i_{L_0} + \dfrac{1}{L} V_{np} + \dfrac{1}{L} u \\ \dfrac{dV_{np}}{dt} = -\dfrac{i_{L_0}}{C_1 + C_2} + V_r + i_d \end{cases} \tag{6}$$

where i_d and V_r are disturbances from neutral line current, capacitor mismatch or power source variation. They can be written by

$$i_d = \frac{1}{C_{N1} + C_{N2}} i_N, V_r = -\frac{C_{N1} - C_{N2}}{2(C_{N1} + C_{N2})} \frac{dV_d}{dt} \tag{7}$$

As pointed out in Zhong et al. (2006), V_r is constant under normal conditions, which means that V_r is relatively small and its impact on the output is limited. With these in mind, we will focus on the in uence of i_N while ignoring the impact of V_r in the process of designing the controller.

If the state variable of the plant is chosen to be $[i_L, V_{np}]^T$ and we let $u_d(t) = \left[i_N, \frac{dV_d}{dt}\right]^T$, then the following state equations can be obtained:

$$\begin{cases} \dfrac{dx(t)}{dt} = Ax(tb) + Bu(t) + B_d u_d(t) \\ y(t) = Cx(t) \end{cases} \tag{8}$$

where

$$A = \begin{pmatrix} -\dfrac{R_0}{L_0} & \dfrac{1}{L_0} \\ -\dfrac{1}{C_{N1} + C_{N2}} & 0 \end{pmatrix}, B = \begin{pmatrix} \dfrac{1}{L_0} \\ 0 \end{pmatrix} \tag{9}$$

$$B_d = \begin{pmatrix} \dfrac{1}{C_{N1} + C_{N2}} & -\dfrac{C_{N1} - C_{N2}}{2(C_{N1} + C_{N2})} \\ 0 & 0 \end{pmatrix}, C = (\,0\ 1\,) \tag{10}$$

3. PROPOSED CONTROL METHOD

3.1 Repetitive Control

Repetitive control is a control strategy based on internal model principle to improve the accuracy of servosystem. The essence of the internal model principle is to implant the input signal into the digital control model into the controller to form a high-precision feedback system, which is used to realize the system output without static difference (Zhou and She (2018)). When the parameters of the system change with time, the internal model effect in the system will be disturbed and affect the control effect, so the amplitude and phase compensation of the control system should be carried out. By means of compensation, the output value of the controlled object has the same internal model as the input value of the system, so that the system can accurately track the input value. Fig. 3 shows the block diagram of repetitive control structure with compensation in which $f(s)$ is a low-pass filter used to improve the robust stability of the system and N is a delay constant.

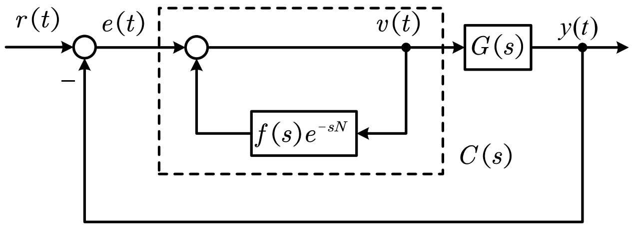


Fig. 3. Block diagram of repetitive control

3.2 Proposed Repetitive Control Method Based on EID

This section will explain the definition of EID before introducing the EID strategy into the repetitive control system.

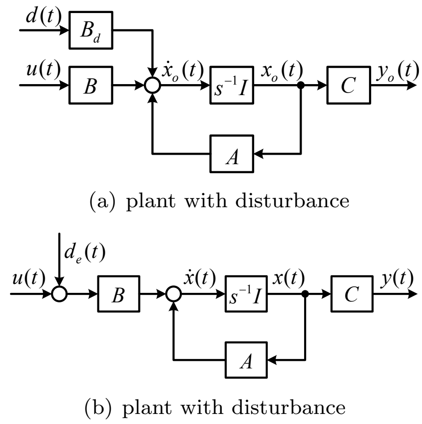


Fig. 4. The concept of EID

EID was first originally proposed by She (She et al. (2008),She et al. (2011)) and further developed by Liu (Liu et al. (2013a), Liu et al. (2013b)). The core idea of EID is to find the equivalent disturbance, $d_e(t)$ in Fig. 4(b) which can have the same influence to the output on the control input channel as the real disturbance $d(t)$, which is shown in Fig. 4(a). Thus, the disturbance $d_e(t)$ is defined as EID.

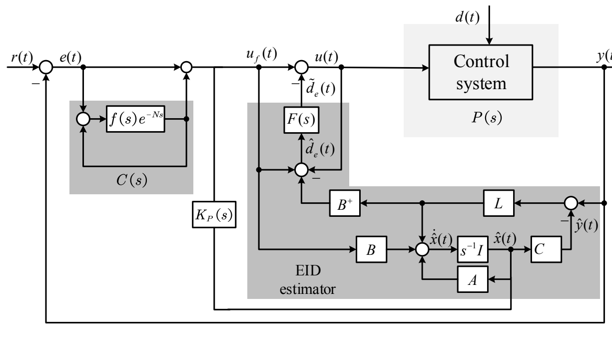


Fig. 5. Block diagram of repetitive control method based on EID

Then we show the structure of the proposed method in Fig.5. The system has five parts: a state observer, the control system, a modified repetitive controller, $C(s)$, an EID estimator , $K_p(s)$, and a feedback compensator.

In the modified repetitive controller, $f(s)$ is a low-pass filter that relaxes the stability condition, and N is the delay time of the controller. The improved repetitive controller is used to reject the periodic neutral-point voltage pulsation.

L is the state observer gain. $F(s)$ is a low-pass filter. The EID estimation is incorporated into the original repetitive control law to improve the disturbance rejection performance of the system.

In Fig. 5, the state observer is

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu_f(t) + L[y(t) - C\hat{x}(t)] \quad (11)$$

Define

$$\Delta x(t) = \hat{x}(t) - x(t) \quad (12)$$

From the above two equations, we obtain

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + \{Bd_e(t) + [\Delta\dot{x}(t) - A\Delta x(t)]\} \quad (13)$$

If there exists a variable, d(t), that satifies

$$\Delta\dot{x}(t) - A\Delta x(t) = B\Delta d(t) \quad (14)$$

Substitute (14) into (11), and define an estimation of the EID, $d_e(t)$, as

$$\hat{d}(t) = d_e(t) + \Delta d(t) \quad (15)$$

Then, we have

$$\dot{\hat{x}}(t) = A\hat{x}(t) + B\left[u(t) + \hat{d}(t)\right] \quad (16)$$

We can solve (17) for $\hat{d}(t)$ and yield

$$\hat{d}(t) = B^+LC[x(t) - \hat{x}(t)] + u_f(t) - u(t) \quad (17)$$

where

$$B^+ = \left(B^TB\right)^{-1}B^T \quad (18)$$

The noise contained in $d_e(t)$ usually influences the control performance of the control system, so the low-pass

filter, $F(s)$, is used to solve this problem. As a result, the filtered estimation of $d_e(t)$, is

$$\tilde{D}(s) = F(s)\hat{D}(s) \quad (19)$$

where $\tilde{D}(s)$ and $\hat{D}(s)$ are the Laplace transforms of $\tilde{d}(t)$ and $\hat{d}(t)$, respectively. The control law is shown as

$$u(t) = u_f(t) - \tilde{d}(t) \quad (20)$$

so as to use $\tilde{d}(t)$ to suppress the impact of $d(t)$. Clearly, the disturbance rejection performance depends on the estimation precision of the EID estimator.

The system depicted in Fig. 5 can be understood as a system involving a repetitive control system and an equivalent input interference system. By applying the small gain theory, the stability conditions of the repetitive control system can be obtained. Then we let

$$G_0(s) = 1 - B^+LC[sI - (A - LC)]^{-1}B \quad (21)$$

$$P(s) = C(sI - A)^{-1}B \quad (22)$$

$$G(s) = K_p(s)P(s) \quad (23)$$

A sufficient stability condition of the whole proposed control system can be given below based on Theorem 1.

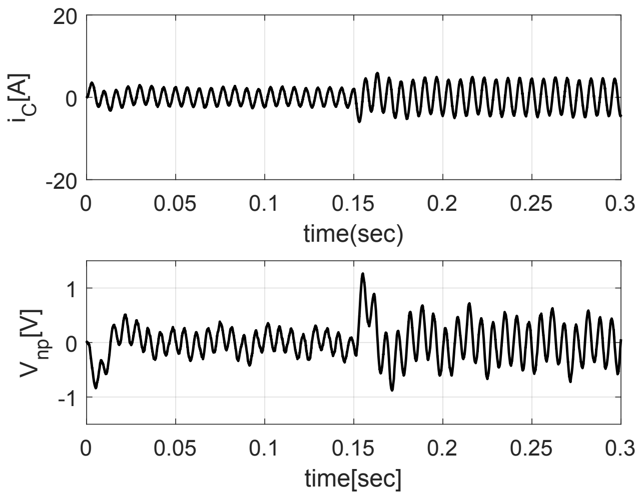


Fig. 6. Neutral circuit waveforms without control

Theorem 1. The EID-based RCS is stable if the following conditions are satisfied

(1) Both $G_0(s)$ and $F(s)$ are stable;
(2) $\|G_0(s)F(s)\|_\infty < 1$;
(3) $[1 + G(s)]^{-1}G(s)\,\epsilon\Re_-$, and no unstable pole-zero cancelation occurs between $K_p(s)$ and $P(s)$; and
(4) $\|f(s)[1 + G(s)]^{-1}\|_\infty < 1$

A detailed proof of $Theorem 1$ is given in Wu et al. (2011), so we omitted the process of proof in this paper.

4. CASE STUDIES

4.1 Case1-Repetitve Control System

In this section, the proposed method is evaluated using MATLAB/SIMULATION software.

Firstly, the effectiveness of the proposed repetitive method is verified. Because the neutral-point pulsation is manifested as the neutral-point current commutes three times in a period, the current disturbance was set to be

$$\begin{cases} i_N = 20\sin(2*150\pi t), 0 < t < 0.15 \\ i_N = 40\sin(2*150\pi t), 0.15 < t < 0.3 \end{cases} \quad (24)$$

The basic parameters of the model are: $L_0 = 2.0mH$, $R_0 = 0.2\Omega$, $C_{N1} = C_{N2} = 5000\mu F$, and $V_d = 800V$.

The time constant of the repetitive controller is usually chosen as the repetitive period of the input signal, we set

$$N = 0.02, f(s) = \frac{150}{s + 150} \quad (25)$$

We conducted and analyzed the following operations.

1) Experiment waveforms without control: Fig. 6 shows the result of the system without neutral-point control, we can see that the neutral-point Vnp deviated largely in this case.

2) Neutral circuit waveforms with proposed repetitive control: the experient results with the proposed repetitive control strategy are shwon in Fig. 7. The waveform quality of its neutral-point voltage is obviously improved compared with that of Fig. 6.

It can be seen from Fig. 7 that the voltage deviation at the neutral point is suppressed to a low level under the repetitive control. However, we know that although the repetitive controller can improve the periodic disturbance suppression performance of the system, the cost of the improvement is to deteriorate the non-periodic signal control performance.

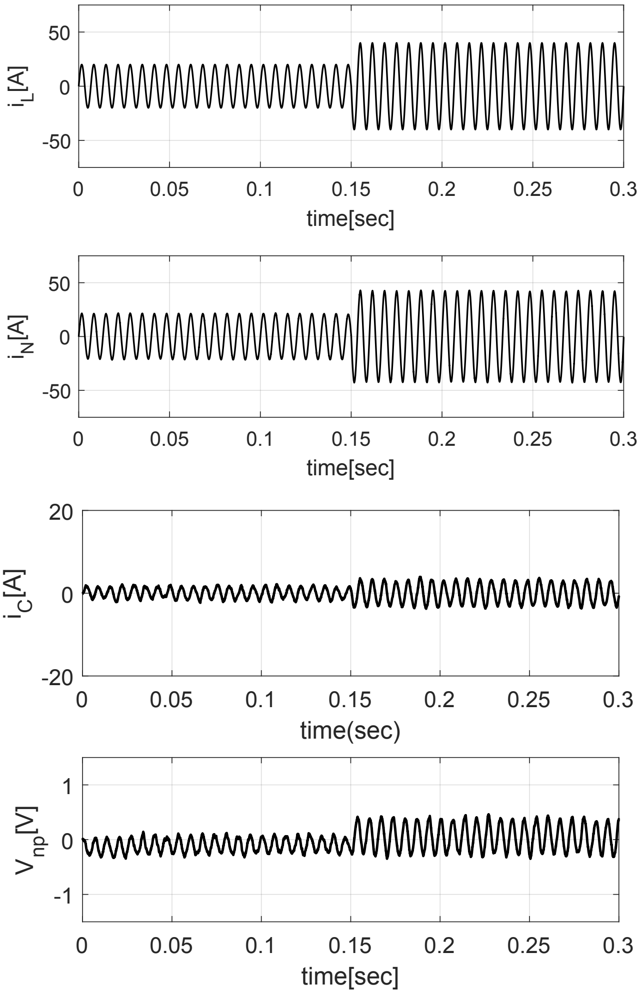


Fig. 7. Neutral circuit waveforms with repetitive control

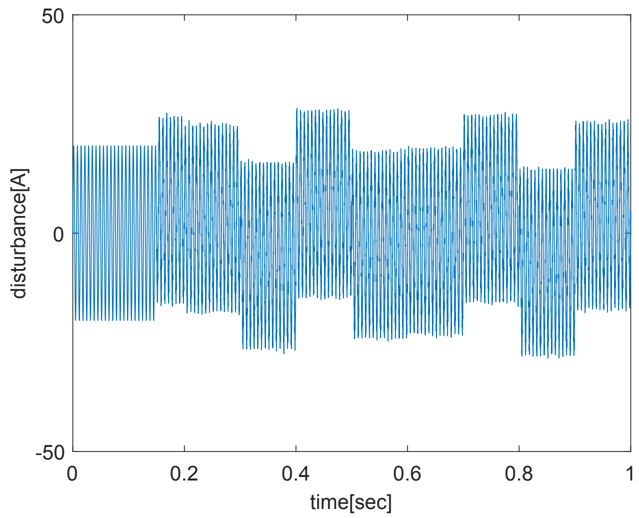
4.2 Case2-Proposed Control Method Base on EID

The traditional repetitive control system cannot suppress the non-periodic disturbance. Thus, we will verify the superiority of the proposed control method in this section. The basic parameters of the model are the same as them in Case1.

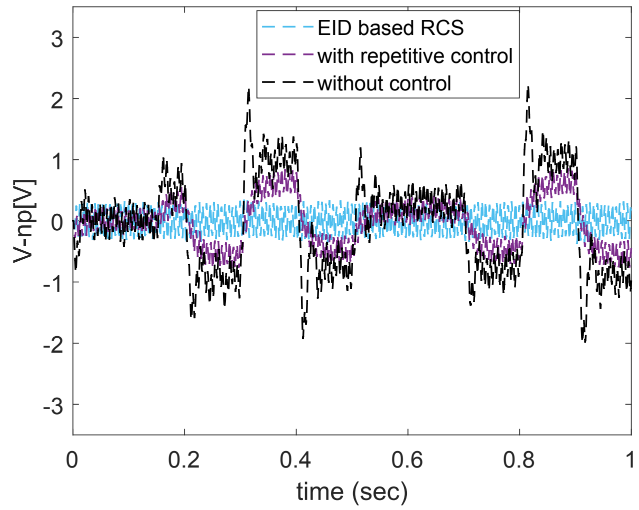
The plant is perturbed by both a repeatable runout disturbance (RRD) and a non-repeatable runout disturbance (NRRD). While the RRD represent the neutral-point voltage pulsation, the NRRD is neutral-point voltage drift. Thus, in this study, the disturbance, $d(t)$, which is a combination of

$$d_1\left(t\right) = 20\sin\left(300\pi t\right) + s\left(t\right), 0 < t < 1 \tag{26}$$

$$d_2(t) = \begin{cases} s\left(t\right), 0 < t < 0.15 \\ 5\sin\left(200\pi t\right) + \tan\left(10\pi t\right) + 0.05, 0.15 < t < 1 \end{cases} \tag{27}$$



(a) disturbance



(b) comparison of simulation results

Fig. 8. Simulation results

where s (t) is the random noise disturbance whose amplitude is less than 1.

Clearly, $d_1(t)$ is an RRD. $d_2(t)$ is the NRRDs. More specifically, $d_2(t)$ is a non-periodic disturbance.

The parameter of the low-filter $F(s)$ was set to be

$$T = 0.001s \tag{28}$$

By using the optimal control theory Liu et al. (2013b), we obtained

$$K_p = [-3.1623\ 3.1598] \tag{29}$$

and the state observer, L, is

$$L = [-2852.0\ 2590.4] \tag{30}$$

Fig. 8(a) represent the disturbance suffered by the system under study, Fig. 8(b) shows the simulation results under three different conditions. When the system is not equipped with neutral-point voltage controller, the voltage at the midpoint uctuates seriously and its maximum value is beyond 2.0 V. Even if the repetitive controller is used for control, the simulation results are still not ideal due to the sacrifice of the non-periodic model control performance to compensate the periodic signal performance. However, We can see that the proposed improved repetitve method achieves the ideal performance in overcoming the voltage fluctuation, the deviation can be reduced by more than 50 percent and damped in the range of [-0.5 0.5] V as shown in Fig. 8(b) by EID compensation. It makes sense to reduce the sensitivity of neutral-point voltage to power changes, especially when inverters are used in smart grids that generate unstable electricity, such as solar and wind power systems.

5. CONCLUSION

The neutral-point voltage control problem of NPC three-level converter is studied. An additional neutral circuit is added to provide neutral current, potentially reducing the size of the dc-link capacitor. Firstly, the voltage control problem at the neutral point is transformed into a disturbance suppression problem by establishing an equivalent linear model of the system. Then the repetitive control and an improved control method based on EID compensation are used respectively. Repetitive control eliminates periodic neutral point pulsation, and EID is applied to compensate the defects of repetitive control and eliminate the neutral-point voltage drift. The anti-interference mechanism of the proposed strategy is expounded. Through the configuration of the control system, Simulation results show the effectiveness and superiority of this method by the comparison of different circumstances and the proposed method has very great robustness.

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