Performance evaluation of model predictive control method for neutral point clamped inverter

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ABSTRACT

The neutral-point clamped (NPC) inverter is a popular three-level converter topology used in motor drive applications and other dc/ac converter systems. In this paper, the performance evaluation of the model predictive control is performed to investigate its applicability in controlling NPC inverters. The model predictive control (MPC) is a promising closed-loop control strategy in applications where multiple control goals are considered. The ease of adding the objectives to the control law improves the reputation of the MPC. The numerous control goals can be regulated in single feedback. Thus, the adequate bandwidth is noticeably higher compared to the traditional linear controllers. However, controlling the multiple objectives require the use of weighting factors to tune the system performance. Regarding the system performance, multiple reference tracking performance is investigated in this study. Our case study considers three control goals: output load current, switching frequency control, and capacitor voltage balancing. The predictive control is designed to regulate these dynamics, and comprehensive performance analyses are performed. The designed controller is tested using a simulation tool. The simulation results prove that predictive control offers an excellent multi-objective control performance provided that the weighting factors and other design parameters are finely adjusted. The poor selection of the design parameters affects the closed-loop performance, and the conducted analyses show the effects of the controller parameters.

1. INTRODUCTION

The neutral-point clamped (NPC) inverters are broadly preferred in ac drive applications and power electronics systems. It is a three-level three-phase inverter that can utilize three different voltage levels ($0.5v_{dc}$, 0, $-0.5v_{dc}$) at the inverter output. This offers a substantial benefit regarding reducing the voltage stress on the active switches. Furthermore, the power level can be doubled due to the half voltage across switching devices. The other important aspect of NPC inverter is that the first few harmonics are centered around the two times higher of the operating frequency (switching frequency) (Klabunde et al. 1994; Nabae, et al. 1981; Rojas et al. 1995). This simplifies the procedure of selecting the filter parameter; thus, more efficient filtering capability is attained. A superior harmonics attenuation is achieved, improving the quality of the controlled variables, such as the output voltage or

current. Besides the topological advantages of NPC inverters, a higher number of active switches is required to utilize the NPC inverter. In a traditional two-level voltage source inverter, only 6 active switches are used.

However, the NPC inverter employs the 12 active switches, and more active switches increase the switching losses. The other critical point is that the control complexity is higher compared to the two-level topologies. In particular, the capacitor voltage balancing must be considered in the controller design process. In the literature, the voltage balancing problem has been reported in several research papers (Jarutus and Kumsuwan, 2017). Different types of strategies have been investigated to overcome the capacitor voltage imbalance problem.

In the literature, different control and modulation strategies have been reported for NPC inverter systems. The optimal switching frequency technique was introduced in (Steinke, 1992). An analytical method to

analyze NPC inverter dynamics and the performance of the capacitor voltage balancing are extensively examined (Ogasawara and Akagi, 1993). A comprehensive stability analysis of neutral-point control (Newton and Sumner, 1997) has been performed, a model that explains the system dynamics has been proposed. Moreover, a predictive control scheme has been introduced in (Vargas et al. 2007), multi-objective optimization problem has been formulated to control NPC inverter. The self-balancing effect has been investigated in (Jie et al. 2011), the effects of the self-balancing on the switching frequency have been reported. Another interesting work (Choi et al. 2015) shows that the voltage oscillations can be reduced by introducing an offset in time to the switch turn-on procedure. Other control mechanisms are also available in the literature. To gain a depth understanding of the NPC system, a good survey paper (Rodriguez et al. 2010) can be referred to.

In this study, the model predictive control method is investigated to analyze the dynamic characteristic of MPC. The control goals are considered the multi-objective optimization problem and the output load current, capacitor voltage balancing, and average switching frequency. The effects of the design parameters are examined, the feasibility of the MPC strategy in controlling NPC inverter is explored. The simulation works verify the system model and the formulated MPC controller. The simulations work demonstrates the potency of the MPC method; however, the design parameters have considerable influences on the steady-state and transient performance.

2. SYSTEM MODEL

In this section, the system mode of the NPC inverter is given. The NPC inverter topology schematic is illustrated in Fig. 1. Each NPC inverter leg has four active switches and two diodes; a high number of switching combinations are possible in this configuration. However, there are some switching restrictions to ensure stable operation. Thus, some of these switching states are not permissible. By considering the switching limitations, the NPC inverter yields 27 allowable switching states. To have a significant sub-set (solution set) allows flexibility in designing the objective function. In NPC inverter, the switching state $S_{j\alpha}$ refers to switching status of phase j, with $j\epsilon$ {a,b,c} and $\alpha \epsilon$ {1,2,3,4}. At the output of the inverter stage, three discrete voltage levels can be generated. The switching state for each phase is summarized in Table 1. The parameter P refers to positive dc voltage, and N refers to negative dc voltage. 0 denotes the zero dc voltage at the output of the inverter stage.

Table 1. The switching states for each phase

S_j	S_{j1}	S_{j1}	S_{j1}	S_{j1}	v_{j0}
P	1	1	0	0	$v_{dc}/2$
0	0	1	1	0	0
N	0	0	1	1	$-v_{dc}/2$
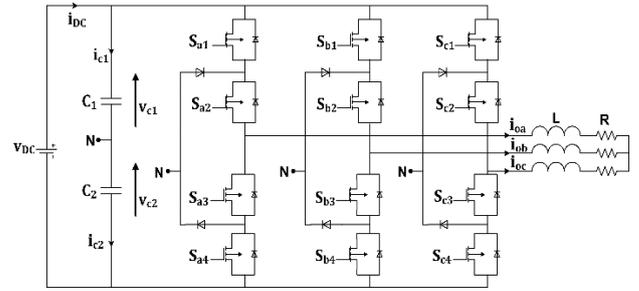
Figure 1. The neutral-point clamped inverter circuit diagram.

Some voltage vectors that the NPC inverter can produce are redundant. Thus, these voltage vectors can be eliminated in the controller design process. The space vector form of the output voltage and current are expressed as

$$\boldsymbol{v_o} = \frac{3}{2}(v_{oa} + \boldsymbol{r}v_{ob} + \boldsymbol{r}^2 v_{oc}) \qquad (1)$$

$$\boldsymbol{i_o} = \frac{3}{2}(i_{oa} + \boldsymbol{r}i_{ob} + \boldsymbol{r}^2 i_{oc}) \qquad (2)$$

where $\boldsymbol{r} = e^{j(2\pi/3)}$. The continuous-time model of the load current is defined as

$$\boldsymbol{v_o} = L\frac{d\boldsymbol{i_o}}{dt} + R\boldsymbol{i_o} \qquad (3)$$

The capacitor voltage dynamic models can be derived as

$$C\frac{dv_{c1}}{dt} = i_{c1} \qquad (4)$$

$$C\frac{dv_{c2}}{dt} = i_{c2} \qquad (5)$$

To acquire the discrete-time model of the control variable, a numerical method can be applied. In this study, the Forward Euler method is used to convert the continuous data to sampled data. The Forward Euler approximation is as follows:

$$\frac{df(t)}{dt} \approx \frac{f(k+1) - f(k)}{T_s} \qquad (6)$$

k denotes the sampling instant. T_s implies the sampling period. By using (6), the discrete-time model of (3) results

$$\boldsymbol{i_o}(k+1) = \left(1 - \frac{RT_s}{L}\right)\boldsymbol{i_o}(k) + \frac{T_s}{L}\boldsymbol{v_o}(k) \qquad (7)$$

In (7), $\boldsymbol{i_o}(k+1)$ is the prediction of the load current, $\boldsymbol{i_o}(k)$ refers to the instantaneous load current measurement, and $\boldsymbol{v_o}(k)$ denotes the output load voltage. By applying the same procedure, the capacitor voltage prediction models are defined as

$$v_{c1}(k+1) = v_{c1}(k) + \frac{1}{C_1}i_{c1}(k)T_s \qquad (8)$$

$$v_{c2}(k+1) = v_{c2}(k) + \frac{1}{C_2}i_{c2}(k)T_s \qquad (9)$$

In (8)-(9), $i_{c1}(k)$ and $i_{c2}(k)$ are the capacitor current measurements. C_1 and C_2 are the capacitance at the inverter input. However, the measurement of these quantities is not a straightforward task (in most cases, the capacitor current measurement is meaningless due to the fast dynamic), $i_{c1}(k)$ and $i_{c2}(k)$ can be estimated by using the dynamic model of the capacitor and NPC inverter. The estimation can be performed based on (10) and (11).

$$i_{c1} = i_{dc}(k) - G_{1a}i_{oa}(k) - G_{1b}i_{ob}(k) - G_{1c}i_{oc}(k) \qquad (10)$$

$$i_{c2} = i_{dc}(k) - G_{2a}i_{oa}(k) - G_{2b}i_{ob}(k) - G_{2c}i_{oc}(k) \qquad (11)$$

where

$$G_{1j} = \begin{cases} 1, & S_j = P \\ 0, & S_j = N \text{ or } 0 \end{cases} \qquad (12)$$

$$G_{2j} = \begin{cases} 1, & S_j = N \\ 0, & S_j = P \text{ or } 0 \end{cases} \qquad (13)$$

with $j \in \{a,b,c\}$. $i_{c1}(k)$ and $i_{c2}(k)$ relies on the switch positions. Thus, they can be estimated using the instantaneous switch positions. As a final comment, the prediction model of the system is derived, and the MPC uses (7)-(11) to predict the control goals.

3. PREDICTIVE CONTROL SCHEME

The predictive controller uses the prediction model of the system to predict the output load currents and the capacitor voltage for each allowable control inputs (27 switching states). The measurements in the MPC control scheme are the output load current, capacitor voltage, dc-bus voltage, and dc-bust current. These four measurements are necessary to apply the predictive control routine. Once the prediction of the control variables process is over, the cost function is evaluated for every legitimate state. The designed objective function is defined as

$$g_{NPC} = g_1 + g_2 + g_3 \qquad (14)$$

where

$$\begin{aligned} g_1 = |i_{oa}^*(k+1) - i_{oa}(k+)|^2 \\ + |i_{ob}^*(k+1) - i_{ob}(k+)|^2 \\ + |i_{oc}^*(k+1) - i_{oc}(k+)|^2 \end{aligned} \qquad (15)$$

$$g_2 = \Gamma_{vc}|v_{c1}(k+1) - v_{c2}(k+1)| \qquad (16)$$

$$\begin{aligned} g_3 = \Gamma_{swc}(|S_{j1}(k+1) - S_{j1}(k)| + \cdots \\ + |S_{j4}(k+1) - S_{j4}(k)|) \end{aligned} \qquad (17)$$

In (14), the term g_1 is responsible for tracking the output load current trajectory. The load current error terms are introduced in g_1 to effectively control the output load current. The term g_2 controls the capacitor voltages; thus, the voltage imbalance problem is solved by the inclusion of g_2 term. Moreover, g_3 is responsible for controlling the switching frequency. In power electronics, the switching loss increases with the switching frequency. Thus, controlling the switching

frequency is highly desirable to achieve an acceptable conversion efficiency. The predictive control scheme is depicted in Fig. 2. Following Fig. 2, the control variables are controlled by assessing the objective function. The switching state that offers a minimum cost of g_{NPC} is picked and applied to the NPC inverter. This feedback algorithm is repeated at every sampling instant k. Therefore, the MPC implementation can be considered as an iterative operation.
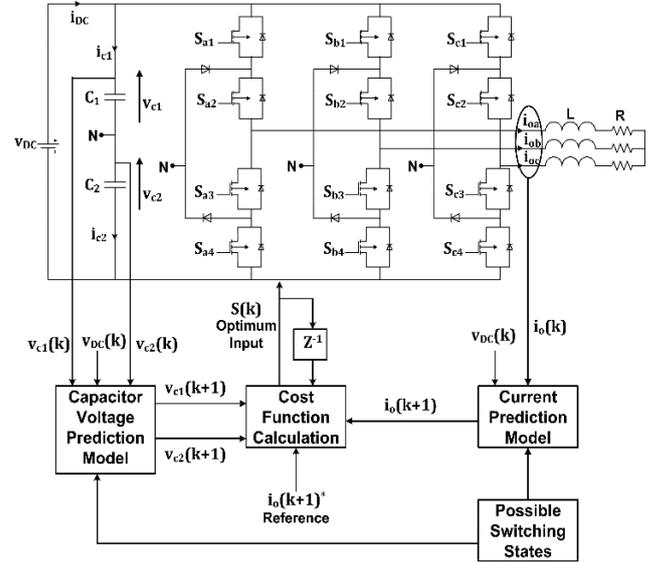

Figure 2. The model predictive control scheme

When $v_{c1}(k+1)$ and $v_{c2}(k+1)$ are equal each other, g_2 results zero. In this case, perfect voltage balancing is achieved. The term g_3 implies that transition from one state to another is penalized. Thus, g_3 has a big influence on the switching frequency reduction. The switching state transition rate is inherently limited due to the penalization term of g_3. The other important design parameters are the weighting factors Γ_{vc} and Γ_{swc}. Γ_{vc} implies the importance of the voltage balancing term. The control of the capacitor voltage equalization becomes more critical as Γ_{vc} increases. Thus, the weighting factors are quite important tuning parameters. The weight Γ_{swc} is the tuning parameter of the switching frequency control term g_3. A large value of Γ_{swc} offers a better switching frequency regulation. In an optimization problem formed by more than one control goal, the weighting factors are required to handle the relationship between control terms. The critical comment on the nomination of these weighting factors is that a good approach to determine the weighting factors has not been proposed yet. In most cases, simulation-based tuning methods are used to determine these tuning parameters.

4. SIMULATION RESULTS AND PERFORMANCE EVALUATION

To perform the performance analyses, the system is simulated using Matlab/Simulink. The simulation parameters are given in Table 2. To assess the steady-state performance, the control variables are monitored. Fig. 3 presents the steady-state waveforms. In this test scenario, the load current reference is 10 A peak with 50

Hz fundamental frequency. According to the steady-state results, the output load current looks good, see Fig. 3(a). The capacitor balancing performance is acceptable, see Fig. 3(b), no big deviation between v_{c1} and v_{c2} is observed.

Table 2. Simulation parameters

Parameters	Description	Values
v_{dc}	dc-bus voltage	380 V
C_1	C_1 capacitance	750 µF
C_2	C_2 capacitance	750 µF
R	Load resistance	5 Ω
L	Load inductance	10 mH
T_s	Sampling period	20 µs
Γ_{vc}	Weighting factor	0.6
Γ_{swc}	Weighting factor	0.05
Solver	Simulink solver	Ode-45
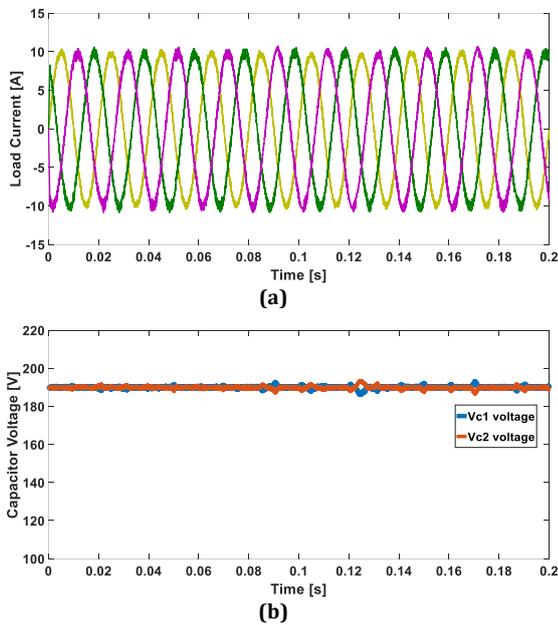
Figure 3. The steady-state waveform of the predictive controller. (a) The output load current waveform (b) Capacitor voltage waveform.
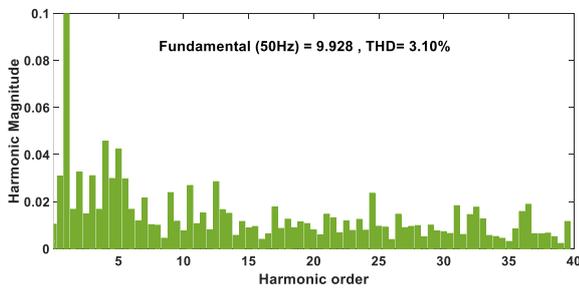

Figure 4. FFT analysis of the load current up to 40th harmonics.

To examine the load current quality, Fast Fourier Transform (FFT) analysis is conducted. The spectral contents are calculated up to 40th harmonics. The frequency spectrum waveform of the output load current is reported in Fig. 4 under steady-state conditions. The load current total harmonic distortions are roughly 3.10%. The calculated THD level is quite acceptable, and

the quality of the load current satisfies the design specifications.

The magnitude of the fundamental frequency (50 Hz) is 9.928 A, close to the reference value of 10 A. To investigate the transient performance of the predictive controller, the load current step is applied to the NPC inverter system. The transient response of the system is reported in Fig. 5. The load current step is applied to 5 A peak to 10 A. The predictive controller gives a quick response to the load variations and compensates for the error. The capacitor voltage control is attained, no unwanted discrepancy is observed. Both capacitor voltage is approximately 190 V which corresponds to half of the dc-bus voltage v_{DC}.
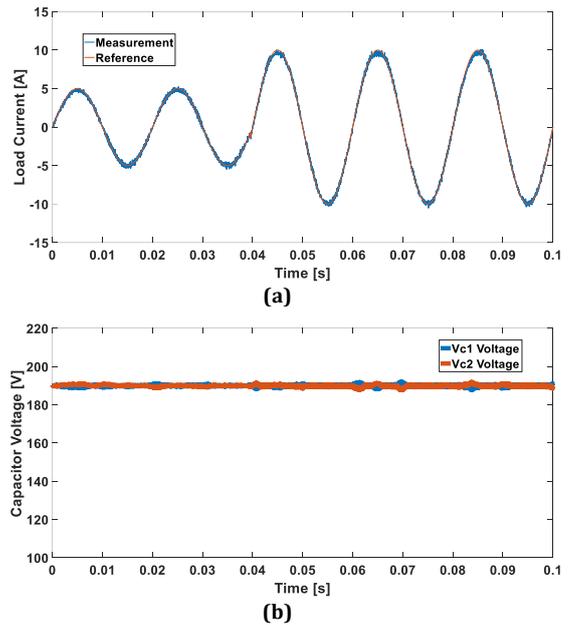

Figure 5. The transient waveform of the predictive controller. (a) The load current waveform (measurement and reference) (b) Capacitor voltage waveform

To explore the weighting factor Γ_{vc} effects on the capacitor voltage balancing performance, Γ_{vc} set as 0. Then, Γ_{vc} has switched to its nominal value of 0.6. When Γ_{vc}=0, the capacitor voltage balancing is ignored by the predictive controller. It means that the capacitor voltage imbalance is not penalized; thus, the capacitor voltages may not be equal. The effect of Γ_{vc} is presented in Fig. 6, and the fine choice of Γ_{vc} remarkably reduces the voltage imbalance. These simulation results prove that the predictive controller performance highly relies on the selected weighting factors.

For Γ_{vc}=0, v_{c2} is approximately 200 V while v_{c1} is 180 V at the same time. This causes voltage imbalance. For Γ_{vc}=0.6, both capacitor voltages approximately equal 190 V.
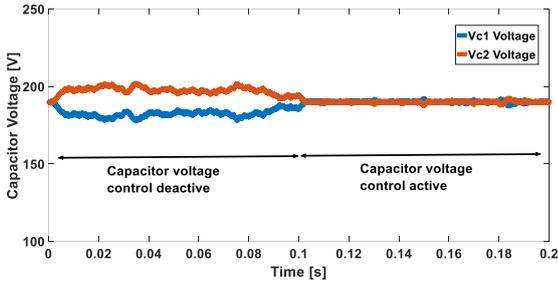
Figure 6. The impacts of the parameter Γ_{vc} on the term $|v_{c1} - v_{c2}|$.
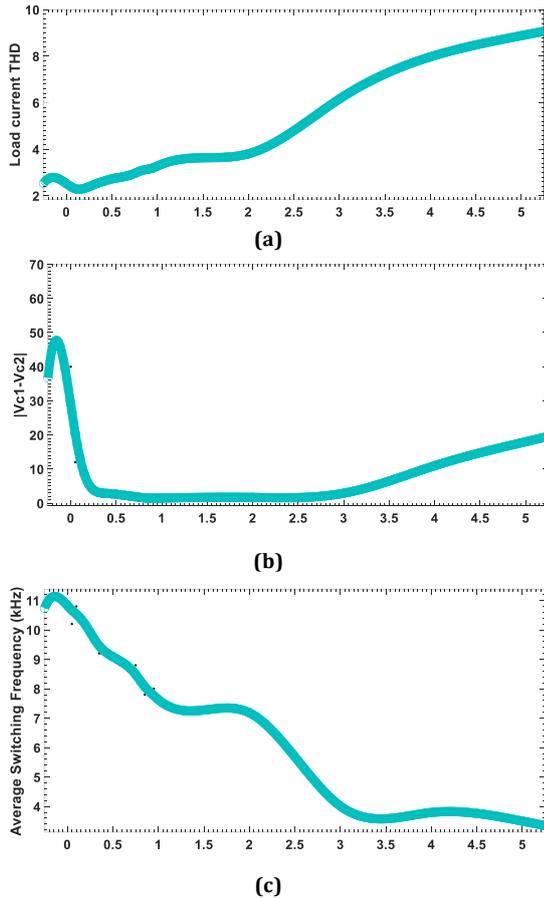
Figure 7. The impacts of the parameter Γ_{vc} on the control variables. (a) The waveform Γ_{vc} vs load current THD. (b) The waveform Γ_{vc} vs. $|v_{c1} - v_{c2}|$. (c) The waveform Γ_{vc} vs. operating frequency.

The effects of the parameter Γ_{vc} on the controller, variables are shown in Fig. 7. The load current has a high THD tendency as Γ_{vc} increases. For the lower choice of Γ_{vc} such as $0.05 < \Gamma_{vc} < 0.8$, the load current THD varies between $2.43\% < $ THD $< 3.1\%$. This THD level is quite acceptable, and it complies with the international standard. However, further, increase in Γ_{vc} degrade the load current quality, see Fig. 7(a). The choice of $\Gamma_{vc} > 2$ has a negative influence on the load current THD. The THD level is drastically increased; thus, the selection of Γ_{vc} is quite critical. The capacitor voltage imbalance is reduced with a higher value of Γ_{vc}. The choice of $0.05 < \Gamma_{vc} < 3$ improves the capacitor voltage control, the parameter $|v_{c1} - v_{c2}|$ varies between 6V and 2.9 V. However, the further increase in Γ_{vc} does not help to improve the control of $|v_{c1} - v_{c2}|$. The voltage imbalance equals 18 V

when Γ_{vc} is selected as 5. The main reason for the practical limit on the capacitor voltage control performance is that a higher value of Γ_{vc} causes the increase in the load current THD. Therefore, the control of the capacitor voltage becomes challenging due to the high distortions. For that reason, Γ_{vc} should be selected such that all control variables remain in the acceptable range. The switching frequency decreases with the increase in Γ_{vc}. Fig. 7 (c) show the mean value of the operating frequency versus the Γ_{vc}. The computed average operating frequency range is within $3.5\text{kHz} < f_{sw} < 11$ kHz. By taking into all analyses results presented in Fig.7, the range within $0.05 < \Gamma_{vc} < 1$ is the sweet spot for Γ_{vc}. The selection of Γ_{vc} within this range offers a good control performance of all control goals. The last evaluation work is performed to analyze the effects of switching frequency control term Γ_{swc}. In this performance assessment process, two control variables are under consideration: the load current THD and the average switching frequency. The effect of Γ_{swc} on the load current, THD, and the mean value of the operating frequency is shown in Fig. 8. The load current THD increases as the value of Γ_{swc} increases. In particular, the selection of $\Gamma_{swc} > 4$ degrades the output load current control performance. The key reason for this harmful effect is that the switching frequency is noticeably reduced with the increase in Γ_{swc}, see Fig. 8 (b). The switching transitions are further penalized by increasing Γ_{swc}. Thus, the NPC inverter does fewer switching transitions resulting in a lower switching frequency. However, the output load current control is negatively influenced. Based on the collected simulation results, the selection of $0.5 < \Gamma_{swc} < 2.5$ is recommended to attain good steady-state performance.
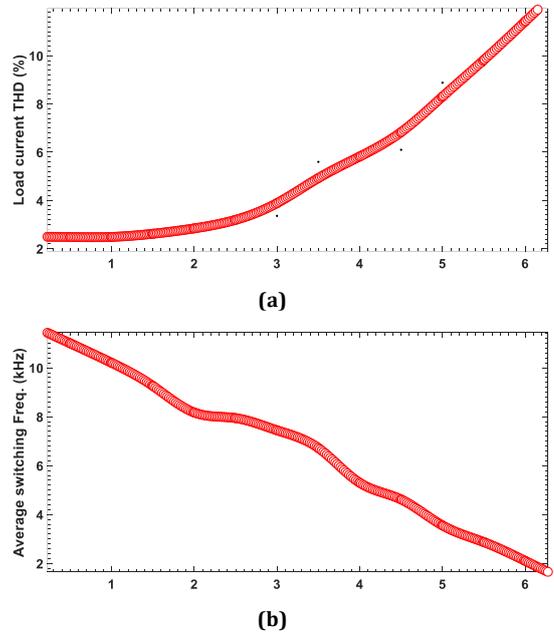
Figure 8. The impact of the tuning parameter Γ_{swc} on the control variables. (a) The waveform Γ_{swc} vs. load current THD. (b) The waveform Γ_{swc} vs. switching frequency.

Finally, the proposed control method is compared with the conventional control technique which is based on the proportional-integral (PI) combined with the

linear modulator. Table 3 summarizes the comparison results. According to Table 3, the proposed method offers faster dynamic response than the conventional method to load perturbations. The transient time is noticeably lower for the proposed strategy. On the other hand, the traditional method provides a lower THD under steady-state performance.

Table 3. Comparison results

Metric	PI+Modulator	MPC
Transient time	210 μs	155 μs
Load current THD	3.05 %	3.10 %
Modulator	Required	No
Inclusion of constraints	No	Yes
Inclusion of nonlinearity	No	Yes
Switching frequency	Fixed	Variable
Design complexity	High	Low
Voltage balancing	Yes	Yes

The PI+modulator requires the linear modulator to generate the gate signals. Thus, the switching frequency is fixed. However, the inclusion of the modulator increases the complexity of the design stage. On the contrary, the MPC strategy does not require a modulator; therefore, the switching frequency varies during the operation. Both control methods offer voltage balancing capability. The other important aspect is that the conventional method does not provide the flexibility to include the nonlinearities or control constraints. On the other hand, the inclusion of the system constraints is relatively easy in the MPC method. Regarding the simplicity of the feedback design, the MPC method has several advantages over the traditional control method.

5. CONCLUSION

This paper has presented the performance evaluation of the predictive control method for the NPC inverter. The performance analyses have been conducted to scrutinize the steady-state performance and transient performance of the MPC. The impacts of the design parameters on the trajectory tracking performance have been substantially analyzed. Several simulation works have been conducted to prove the effectiveness of the MPC in handling the multi-control objectives. The simulation results demonstrate that multiple-control goals are effectively regulated, and the NPC inverter provides a robust system operation. The choice of the weighting factor highly influences the error compensation performance. Thus, weighting factors should be finely selected to achieve a reliable energy conversion operation.

Author contributions

Ozan Gulbudak: Design and analyses, Methodology **Mustafa Gokdag:** Simulation, Writing-Original draft preparation.

Conflict of interest

The authors declare no conflicts of interest

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