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Research paper

A New Hybrid Predictive-PWM Control for Flying Capacitor Multilevel Inverter

P. Hamedani [*]***, M. Changizian***
Department of Railway Engineering and Transportation Planning, University of Isfahan, Isfahan, Iran.

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[*]Corresponding Author's Email Address:
p.hamedani@eng.ui.ac.ir

Abstract

Background and Objectives: Model predictive control (MPC) is a practical and attractive control methodology for the control of power electronic converters and electrical motor drives. MPC has a simple structure and enables the simultaneous consideration of different objectives and constraints. However, when applying MPC for multilevel inverters (MLIs), especially at higher voltage levels, the number of switching states dramatically increases. This issue becomes more severe when MLIs are used to supply electrical motor drives.
Methods: This paper proposes three different MPC strategies that reduce the number of iterations and computation burden in a 3-phase 4-level flying capacitor inverter (FCI). Traditional MPC with a reduced number of switching conditions, split MPC, and hybrid MPC-PWM control are investigated in this work.
Results: In all methods, the capacitor voltages of the FCI are balanced during different operational conditions. The number of iterations is reduced from 512 in traditional MPC to at least 192 in the split MPC. Moreover, the split MPC strategy eliminates the usage and optimization of weighting factors for capacitors voltage balance. However, in the hybrid MPC-PWM control method in comparison to other methods, the voltage balancing time is much lower, the phase current tracks the reference more accurately, the transient time is lower, and the efficiency is higher. In addition, the capacitors voltage ripple is negligible in the hybrid MPC-PWM control method.
Conclusion: Simulation results manifest the effectiveness of the suggested hybrid MPC-PWM methodology. Results manifest that the hybrid MPC-PWM control offers perfect dynamic characteristics and succeeds in maintaining the voltage balance during different operational conditions.

Introduction

In recent years, different industries, such as electric transportation, have trended to increase the DC-link voltage to yield significant advantages [1]-[2] such as more machine efficiency, less charging time of batteries, lower cable weight, cost reduction, and lower loss [3]-[6]. However, by increasing the DC-link voltage, some drawbacks appear. In two-level inverters, increasing the DC-link voltage results in a higher dv/dt, reduction of the machine lifetime, higher electromagnetic interference (EMI), more eddy current loss in the cores, and more skin effect losses in the windings. When higher DC-link voltage is aimed, replacing the two-level inverter with a multilevel structure can reduce dv/dt and enable the usage of low-voltage switches. In addition, MLIs benefit from various aspects of a system, such as less total harmonic distortion (THD) of current and voltage waveforms, reduced EMI, higher efficiency, more fault-tolerance, more reliability, and lower cooling system size [7]-[10]. The mentioned advantages make multilevel inverters attractive for high-power applications.

In [11], the necessity of increasing the voltage levels in multilevel inverters with higher DC-link voltages is investigated. In this work, the efficiency has been optimized according to power density, and the essential level numbers of an 800 V DC-link flying capacitor inverter are specified. Results prove that for moving from 400 V to 800 V DC-link, to achieve the same efficiency as a two-level 400 V DC-link inverter, a minimum seven-level inverter is needed [11].

In [9], a comprehensive review of MLI structures for traction application is reported. Neutral-point clamped (NPC) inverter, cascaded H-bridge (CHB) inverter, FC inverter, and modular multilevel converter (MMC) are the most utilized multilevel topologies in industrial applications. In [12], the appropriate control techniques for different multilevel structures are discussed and compared. Scaler control [13], Direct Torque Control (DTC) [14], Field Oriented Control (FOC) [15], and MPC [16] are well-known control strategies in AC motor drives with multilevel inverters.

In recent years, MPC has become an appealing control strategy in electrical motor drives due to its interesting advantages [17]-[19]. MPC has a simple implementation and offers the possibility to control several objectives and restrictions in the cost function [21]-[27]. In new investigations, MPC has been utilized to control MLIs [28]-[34]. The application of MPC for MLIs enables the regulation or optimization of various objectives such as load current [35], voltage balancing of the DC capacitors [36], switching frequency [37], inverter switching loss [38], and grid-side reactive power [35].

The main implementation issue of MPC in an MLI is the high number of switching states in which the cost function should be calculated. This increases the computation burden. Therefore, recently, various methods have been suggested for decreasing the computation burden in MLIs with MPC [39]-[47]. Moreover, when implementing the MPC for an MLI, the mathematical computation burden increases even more. This, in turn, restricts the practical utilization of MPC for an MLI. This work suggests a new hybrid MPC-PWM control method for a 3-phase 4-level FCI. The main advantage of this method in comparison with the traditional finite control set MPC (FCS-MPC) is the reduced computation burden.

Mathematical Model of 4-Level FCI

Fig.1 represents the topology of the 4-level FCI. Six IGBT switches with anti-parallel diodes and three capacitors are utilized to generate four voltage levels. The switches are arranged in two groups, up and down. The up and down switches should receive complementary firing pulses to avoid short circuit in the input DC source. The capacitors are charged with a voltage ratio equal to $v_{x1}:v_{x2}:v_{x3}=1:2:3$, with $x\in\{a,b,c\}$. In a 4-level FCI, 2^3=8 different switching states exist for each phase, and 8^3=512 different switching conditions exist in the three-phase 4-level FCI. Table 1 shows all feasible switching conditions of the single-phase 4-level FCI and the related voltage level. The final voltage values of the capacitors are:

$$v_{c1}^* = V_{dc}/3 \quad \text{and} \quad v_{c2}^* = 2V_{dc}/3 \tag{1}$$

In the three-phase 4-level FCI, the voltages of capacitors are:

$$v_{1x}(t) = \frac{1}{C_{1x}}\int_0^t i_x(S_{2x}-S_{1x})(\tau)d\tau + v_{1x}(0) \tag{2}$$

$$v_{2x}(t) = \frac{1}{C_{2x}}\int_0^t i_x(S_{3x}-S_{2x})(\tau)d\tau + v_{2x}(0) \tag{3}$$

where, v_{jx} is the capacitor voltage in cell $j\in\{1,2,3\}$ in phase $x\in\{a,b,c\}$. i_x is the current in phase x. Moreover, S_{jx} is the switching state of the *j*-th IGBT switch *j* in phase *x* (as shown in Fig. 1(a)).

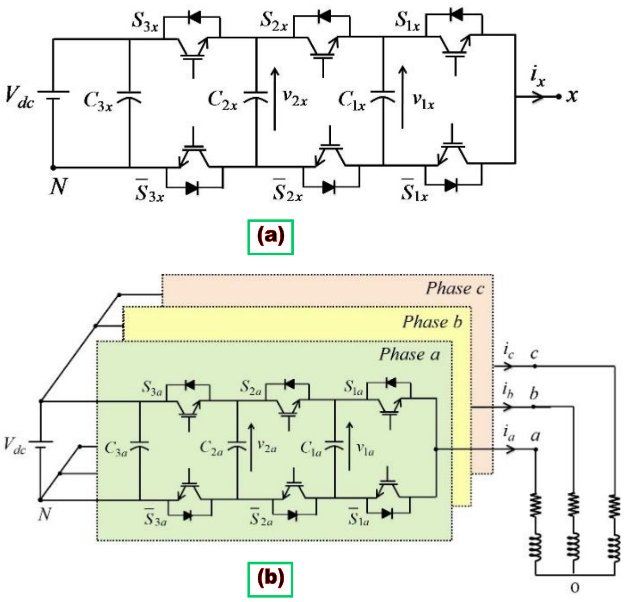

Fig. 1: Structure of 4-level FCI: a) single-phase, b) three-phase.

According to Fig. 1(b), the voltage equation of the output terminal *x* and the FCI neutral point *N* can be expressed as:

$$v_{xN}(t) = S_{3x}V_{dc} - (S_{3x}-S_{2x})v_{2x}(t) - (S_{2x} - S_{1x})v_{1x}(t) \tag{4}$$

while

$$v_{xN} = Ri_x + L\frac{di_x}{dt} + \frac{1}{3}(v_{aN}+v_{bN}+v_{cN}) \tag{5}$$

in which *R* and *L* are the load resistance and inductance, respectively.

Discretization of (2)-(3) using the Euler forward approximation gives:

$$v_{1x}(k+1) = v_{1x}(k) + \frac{T_s}{C_{1x}} i_x(S_{2x}-S_{1x}) \tag{6}$$

$$v_{2x}(k+1)=v_{2x}(k)+\frac{T_s}{C_{2x}}\,i_x\,(S_{3x}-S_{2x}) \quad (7)$$

in which k+1 is the next sampling instant and T_s is the sampling time.

Table 1: Switching states of the 4-level FCI

State	Output Voltage Level	Switching Pulse S_{1x}	S_{2x}	S_{3x}
1	0	0	0	0
2	$\frac{V_{dc}}{3}$	0	0	1
3		0	1	0
4		1	0	0
5	$\frac{2V_{dc}}{3}$	0	1	1
6		1	0	1
7		1	1	0
8	V_{dc}	1	1	1

Model Predictive Control in 4-Level FCI

Fig. 2 shows the block diagram for the conventional MPC of a 4-level FCI. Using the three-phase voltage and current values, the load voltage and current can be written as a space vector:

$$\boldsymbol{v}=\frac{2}{3}(v_{aN}+\boldsymbol{a}\,v_{bN}+\boldsymbol{a}^2\,v_{cN}) \quad (8)$$

$$\mathbf{i}=\frac{2}{3}(i_a+\boldsymbol{a}\,i_b+\boldsymbol{a}^2\,i_c) \quad (9)$$

where $\boldsymbol{a}=\ e^{j2\pi/3}=-\frac{1}{2}+j\frac{\sqrt{3}}{2}$.

The future value of the load current can be calculated as:

$$\boldsymbol{i}^p(k+1)=\left(1-\frac{RT_s}{L}\right)\boldsymbol{i}(k)+\frac{T_s}{L}\,\boldsymbol{v}(k) \quad (10)$$

Using Clark's transformation, α and β axis currents can be extracted from the three-phase currents:

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix}=\frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (11)$$

$$\mathbf{i}=i_\alpha+ji_\beta \quad \text{and} \quad \boldsymbol{i}^p=i_\alpha^p+ji_\beta^p \quad (12)$$

where f can be the reference and predicted current values.

The cost function can be defined as:

$$g=g_i+\lambda\sum_{x=a}^{c}g_{v_x} \quad (13)$$

where

$$g_i=\left|i_\alpha^*(k+1)-i_\alpha^p(k+1)\right|+\left|i_\beta^*(k+1)-i_\beta^p(k+1)\right| \quad (14)$$

$$g_{v_x}=\left(v_{c1}^*-v_{1x}(k+1)\right)^2+\left(v_{c2}^*-v_{2x}(k+1)\right)^2 \quad (15)$$

where λ_v is the weighting factor that adjusts the capacitors voltages and $x\in\{a,b,c\}$. Moreover, v_{c1}^* and v_{c2}^* are the final capacitors voltages given in (1). For finding the minimum of the cost function g specified in (13), MPC examines all 512 possible switching conditions explicitly. The prediction of currents, capacitors' voltages, and cost function are repeated frequently in each sampling instant.

Implementation of the MPC strategy for a 4-level FCI requires a large number of computations. Consequently, the control algorithm will have a significant time delay in practice. To moderate the computational delay, the delay compensation strategy is applied in this work. Fig. 3 shows the flowchart of the MPC strategy for a 4-level FCI with delay compensation. In this method, first, the present values of load current are measured and utilized to estimate the predicted currents at k+1 step time. The switching states are predicted in a shifted forward step time:

$$\boldsymbol{i}^p(k+2)=\left(1-\frac{RT_s}{L}\right)\boldsymbol{i}(k+1)+\frac{T_s}{L}\,\boldsymbol{v}(k+1) \quad (16)$$

Consequently, the cost function can be expressed as:

$$g_v=\left|i_\alpha^*(k+2)-i_\alpha^p(k+2)\right|+\left|i_\beta^*(k+2)-i_\beta^p(k+2)\right| \quad (17)$$

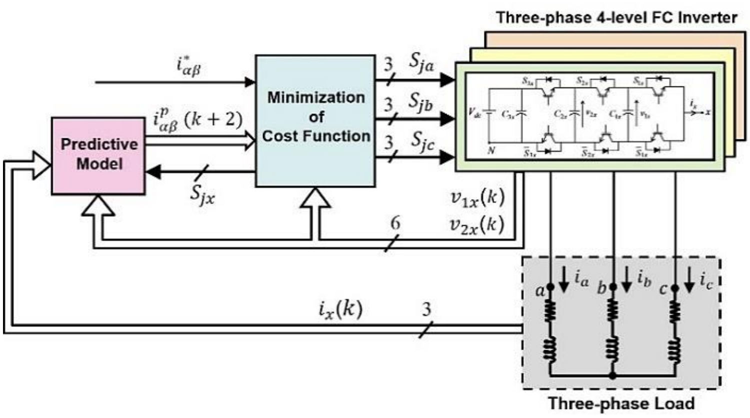

Fig. 2: Block diagram of the conventional MPC of 4-level FCI.

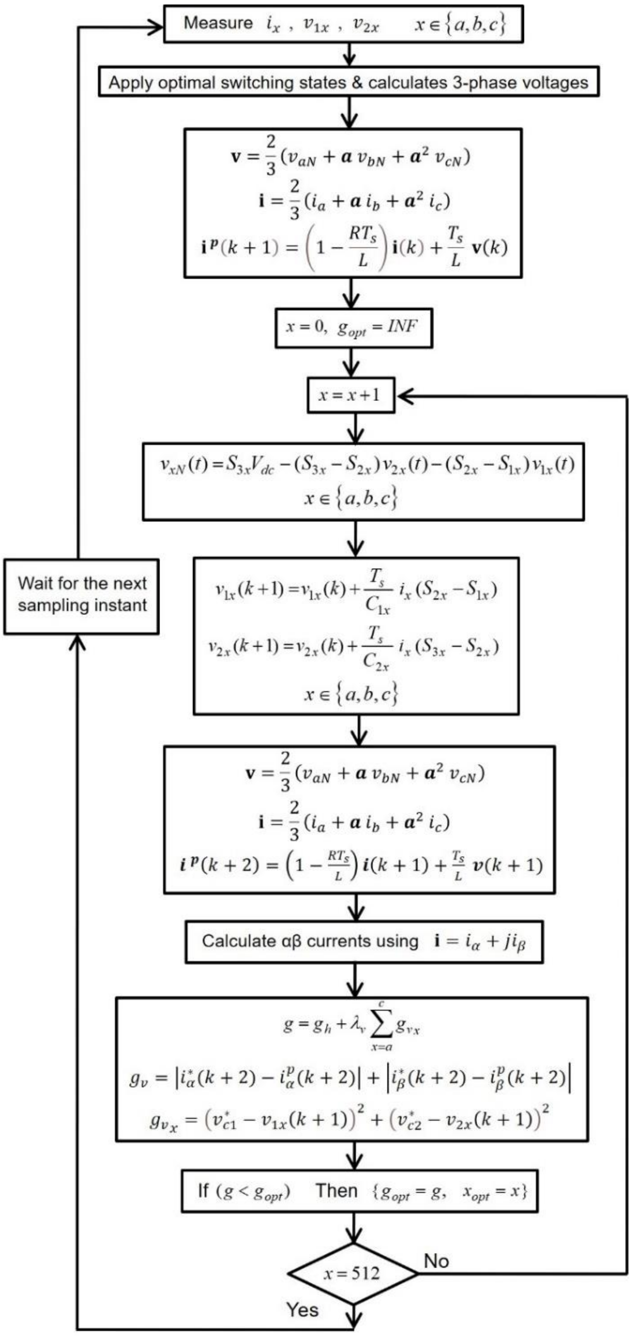

Fig. 3: Flowchart of the conventional MPC of a 4-level FCI.

Split MPC Strategy

To decrease the computation burden in the MPC of multilevel inverters, a new MPC method can be utilized. This method is based on the redundant states in the switching pattern of multilevel inverters. As shown in Table 1, for a 4-level FCI, three redundant stages exist in each medium level of the output voltage. It should be noted that these redundant states can be applied in the split MPC method only if the capacitor voltages reach approximately their desired values.

In the split MPC method, optimization of the objective function is divided into two separate stages. In the first stage, the tracking capability of the load currents is evaluated and optimized. In the second stage, the voltages of the capacitors are balanced. In the next step of the split MPC algorithm, the cost function can be considered the same as g_i in (14). Seeking all possible voltage levels of the output voltages and using (16), the optimum value of g_i is determined, and accordingly, the desired output voltage levels are selected. These voltage values are then considered as the input of the next stage. In the next stage, if the desired output voltage levels are equal to each of the medium voltage levels, i.e., $V_{dc}/3$ or $2V_{dc}/3$, the related redundant states of that level will be sought to balance the capacitors voltages. In the next stage of this method, the cost function can be considered the same as g_{v_x} in (15), and the required voltages of the capacitors are calculated from (6)-(7). In this stage, each phase can be controlled independently to produce the optimal switching pulses, which balance the capacitor voltages. Fig. 4 represents the overall control diagram for the suggested split MPC of the 4-level FCI. Fig. 5 represents the flowchart of the split MPC method for a 4-level FCI with delay compensation.

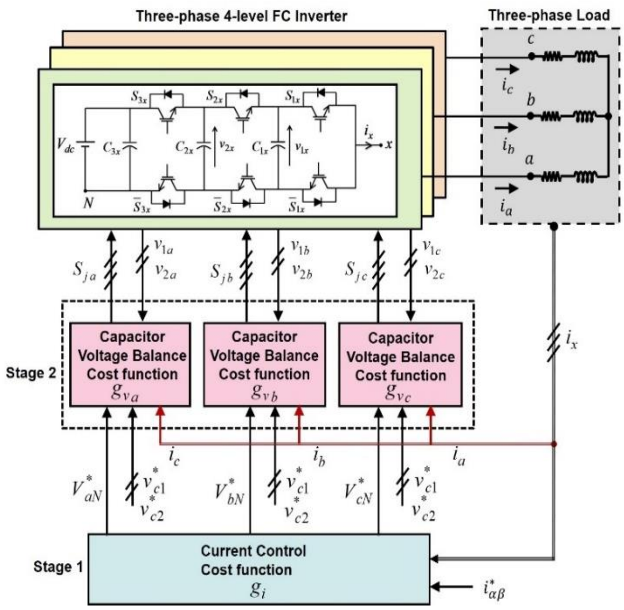

Fig. 4: The control scheme for the split MPC of a 4-level FCI.

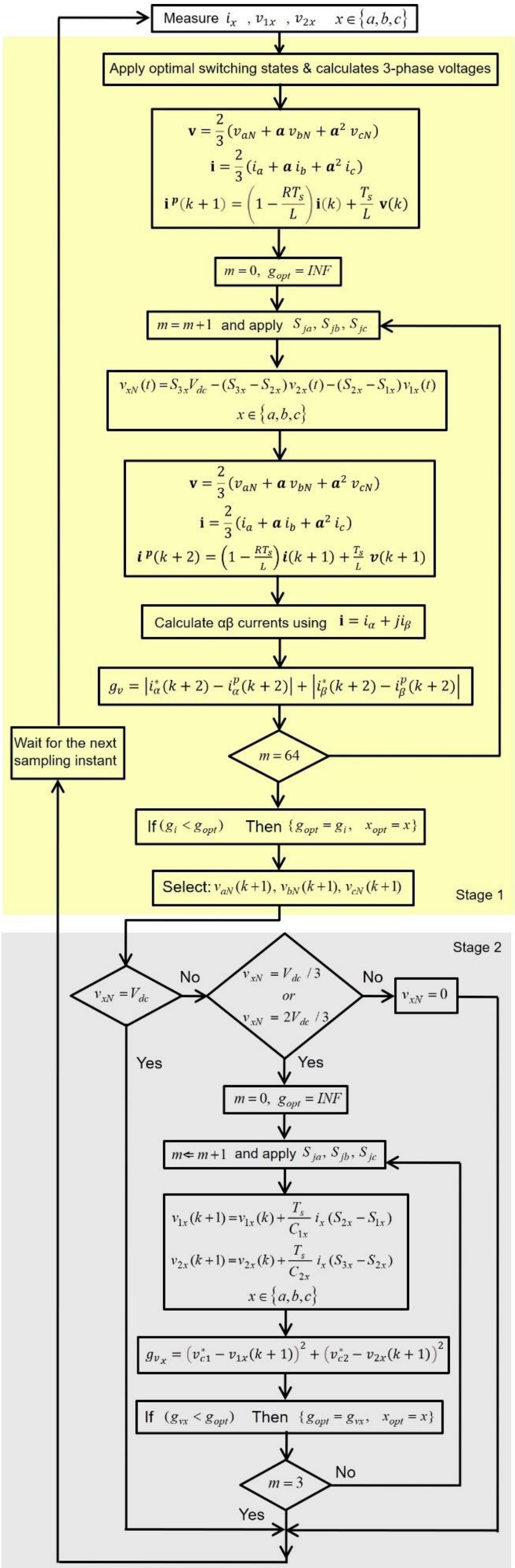

Fig. 5: Flowchart of the split MPC of 4-level FCI.

A Hybrid PWM Linear Control with Voltage Balancing Based on MPC

Fig. 6 shows the block diagram of the hybrid PWM (Pulse Width Modulation) control based MPC for voltage balancing of the 4-level FCI. In this strategy, the capacitors voltages cannot reach their desired values. Therefore, a voltage balancing algorithm is utilized based on model predictive control. Fig. 7 shows the voltage balancing algorithm for the PWM linear control of the 4-level FCI.

Results and Discussion

To investigate the correctness of the proposed hybrid MPC strategy, simulation of a 4-level FCI has been carried out using Matlab/Simulink controlled by MPC with a reduced number of switching conditions, split MPC, and hybrid MPC method.

A list of parameters used in simulation is provided in Table 2. In the traditional MPC, the λ weighting factor is set at λ=0.1.

Fig. 8 demonstrates the reference and actual current in the 4-level FCI by MPC with a reduced number of switching conditions, split MPC, and hybrid MPC-PWM control, respectively.

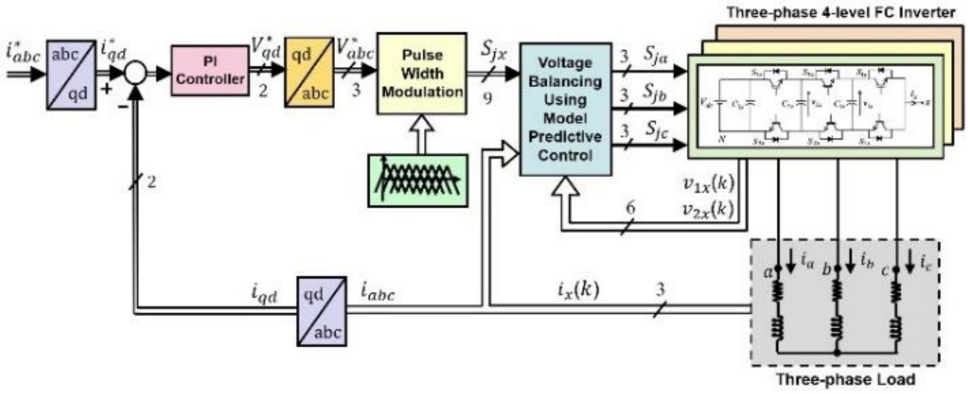

Fig. 6: The block diagram of the hybrid MPC-PWM control of a 4-level FCI.

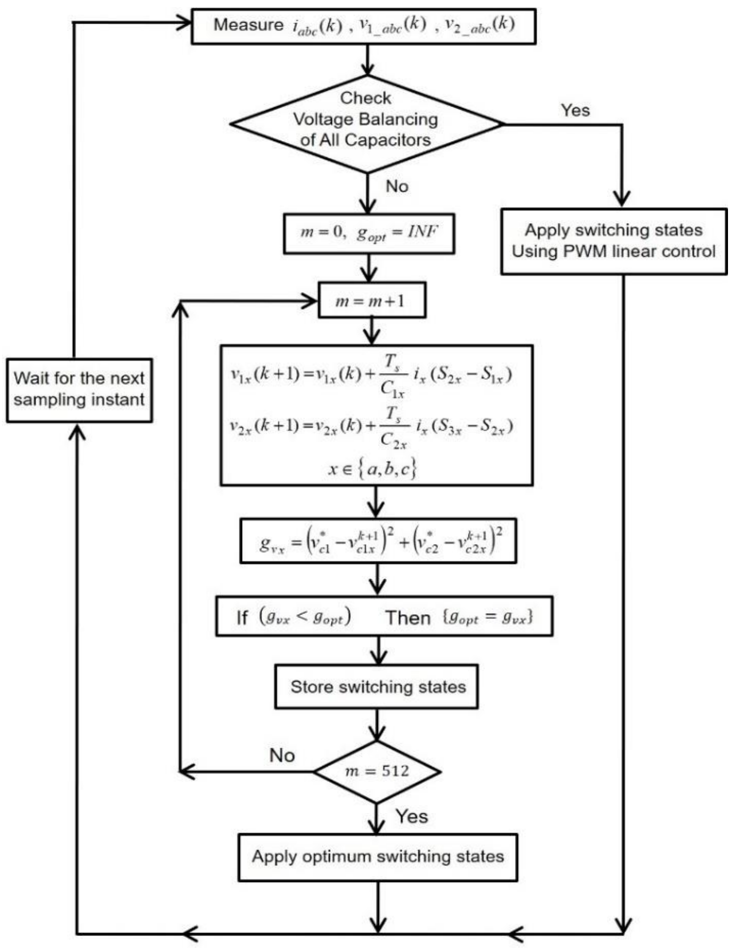

Fig. 7: Flowchart of the voltage balancing using the hybrid MPC-PWM method of a 4-level FCI.

Table 2: Simulation parameters of the 4-level FCI

Parameter	Value
V_{dc}	150 [V]
C_1, C_2	680 [µF]
R	10 [Ω]
L	10 [mH]

It is clear that in the hybrid MPC-PWM control method the phase current tracks the reference more accurately than in other methods. Fig. 9 shows the capacitors voltages in the 4-level FCI by MPC with a reduced number of switching conditions, split MPC, and hybrid MPC-PWM control, respectively. As can be seen, in all methods, the capacitors voltages of the 4-level FCI are balanced during different operational conditions. However, in the hybrid MPC-PWM control method, the voltage balancing time is much lower than in other methods and the capacitors voltage ripple is negligible.

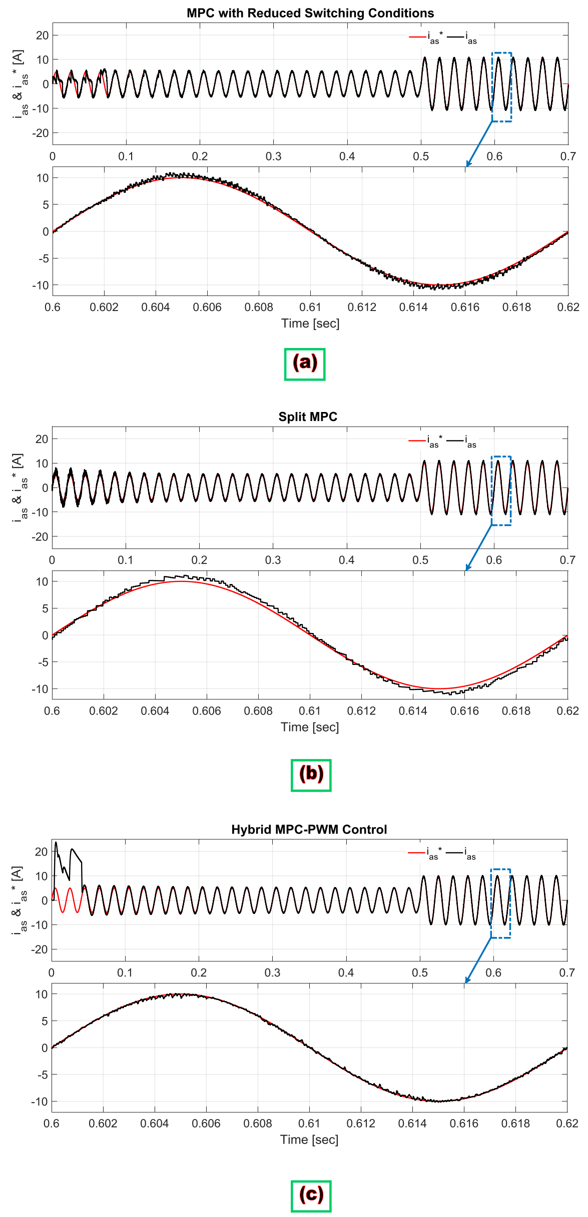

Fig. 8: Reference and actual current in the 4-level FCI: a) MPC with a reduced number of switching conditions, b) Split MPC, c) Hybrid MPC-PWM control.

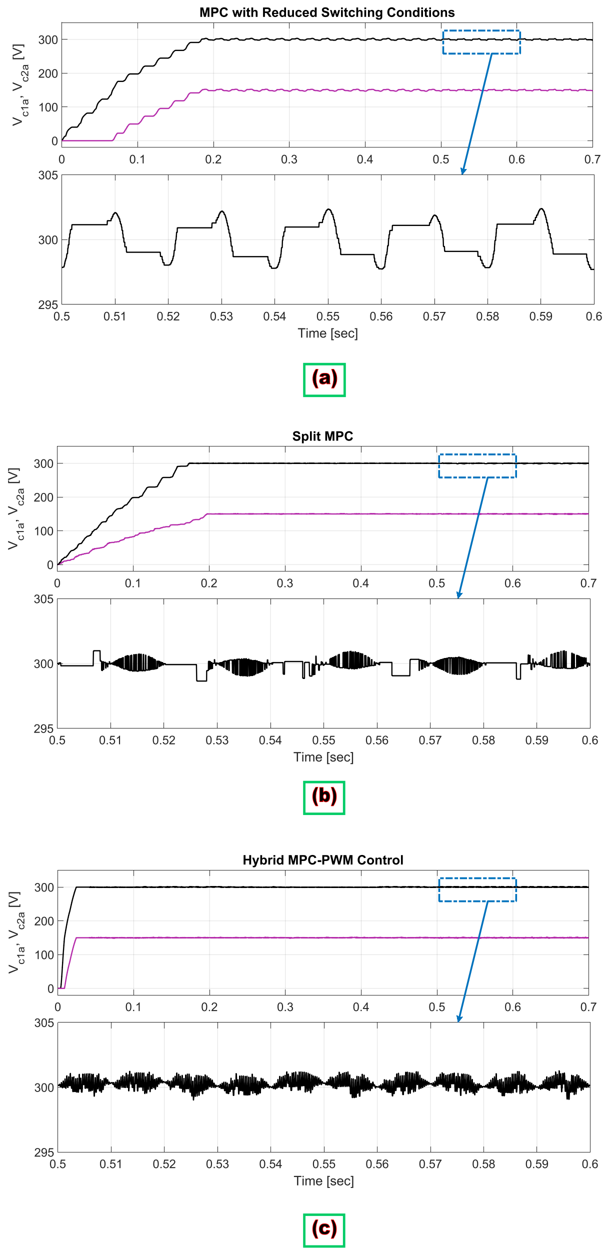

Fig. 9: Capacitors voltages in the 4-level FCI: a) MPC with a reduced number of switching conditions, b) Split MPC, c) Hybrid MPC-PWM control.

Fig. 10 illustrates the three-phase currents, the line voltage (V_{ab}), and the terminal voltage relative to the neutral point O (V_{ao}) in the 4-level FCI by MPC with a reduced number of switching conditions, split MPC, and hybrid MPC-PWM control, respectively. It is evident that in the hybrid MPC-PWM control strategy, the transient time is lower than in other methods. Fig. 11 illustrates the comparison of efficiency versus switching frequency in the 4-level FCI by MPC with a reduced number of switching conditions, split MPC, and hybrid MPC-PWM control, respectively. For calculation of the efficiency, first the total loss and the input power of the FCI is computed in the average switching frequency. The simulations are performed in PLECS software. The utilized IGBTs are IKW40N65ET7 manufactured by Infineon.

The IKW40N65ET7 is a 650 V, 40 A IGBT with anti-parallel diode. For calculating the total loss of the FCI, the conduction loss and switching loss are calculated for all the IGBTs and diodes.

As is evident, for the switching frequencies between 3 KHz to 5.5 KHz, the hybrid MPC-PWM control method results in higher efficiency than other methods. This is because the switching and conduction losses of the FCI are lower in the hybrid MPC-PWM control method.

In Table 3, a quantitative comparison of different control methods for the 4-level FCI is presented for switching frequency around 4 KHz.

According to the results, in the hybrid MPC-PWM control method, the voltage balancing time and the current THD value are significantly lower than in the traditional MPC with a reduced number of switching conditions and the split MPC methods. Furthermore, the phase current tracking performance is more accurate in the hybrid MPC-PWM control method in comparison to other methods. The capacitors voltage ripple is low in the hybrid MPC-PWM and the split MPC methods.

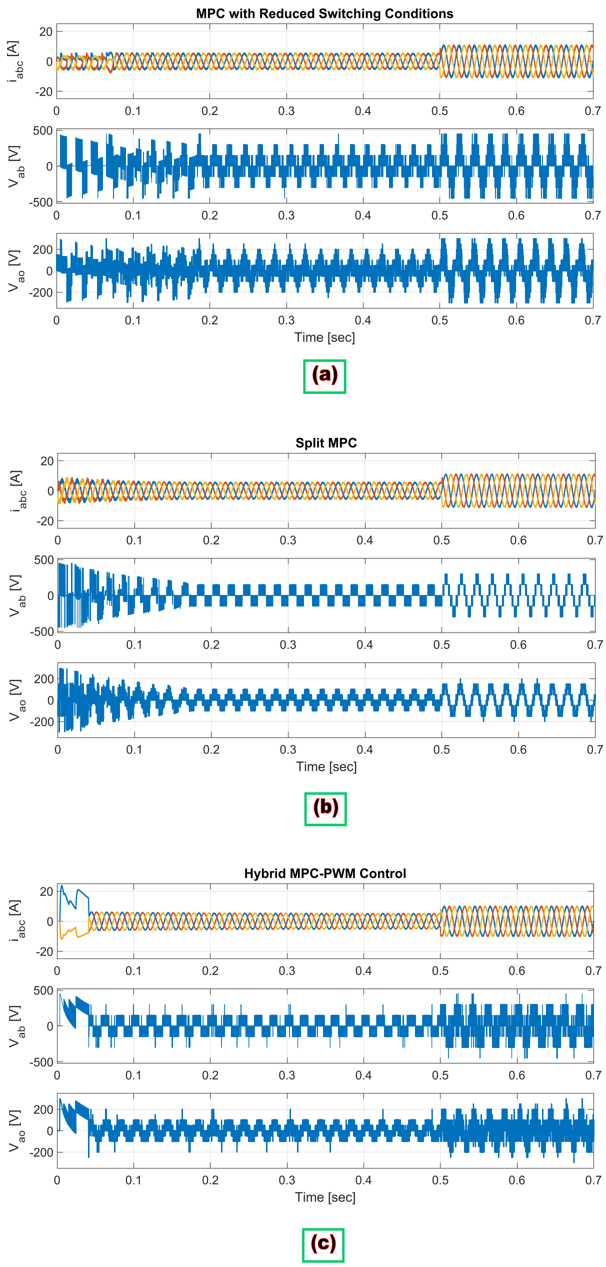

Fig. 10: Three-phase currents, line voltage (V_{ab}), terminal voltage relative to the neutral point O (V_{ao}) in the 4-level FCI: a) MPC with a reduced number of switching conditions, b) Split MPC, c) Hybrid MPC-PWM control.

Conclusion

This work suggests a new hybrid MPC-PWM control method for reducing the number of iterations and computation burden in a 3-phase 4-level FCI. In this strategy, the capacitors voltages of the 4-level FCI are balanced during different operational conditions. The number of iterations is decreased compared to the traditional MPC. Moreover, in the hybrid MPC-PWM control method compared to the traditional MPC with a reduced number of switching conditions and the split MPC, the voltage balancing time is much lower, the phase current tracks the reference more accurately, the transient time is lower, and the efficiency is higher. At the same time, the capacitors voltage ripple is low in the hybrid MPC-PWM control method. Simulation results validate that the proposed strategy achieves similar excellent dynamic behavior and voltage balance as the traditional MPC, but with a relatively reduced number of iterations and computation burden.

Table 3: Comparison of Different Methods for the 4-level FCI

Method	MPC with RSC	Split MPC	Hybrid MPC-PWM
Voltage Balancing Time [sec]	0.1	0.1	0.024
Current Tracking Performance	Medium	Medium	Good
Max. Current Overshoot [A]	4.19	4.05	23.8
Capacitor Voltage Ripple [%]	1.8	1.1	1.2
Current THD [%]	1.10	2.18	0.53
Inverter Losses [Watt]	35.34	34.69	35.63
Efficiency [%]	95.15	95.10	95.15
Average Switching Frequency [KHz]	4.31	4.36	4.19
Sampling Time [μsec]	35	45	100

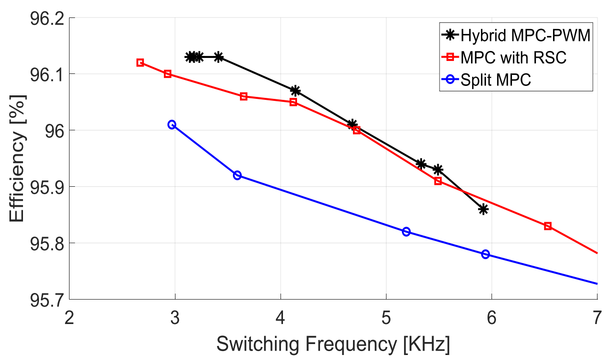

Fig. 11: Comparison of efficiency versus switching frequency for different control methods in the 4-level FCI.

Author Contributions

P. Hamedani carried out the simulation results. M. Changizian interpreted the results. P. Hamedani wrote the manuscript.

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Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

Abbreviations

EMI	Electromagnetic Interference
FCI	Flying Capacitor Inverter
MLI	Multilevel Inverter
MPC	Model Predictive Control
PWM	Pulse Width Modulation
THD	Total Harmonic Distortion

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Biographies

Pegah Hamedani was born in Isfahan, Iran, in 1985. She received B.Sc. and M.Sc. degrees from University of Isfahan, Iran, in 2007 and 2009, respectively, and the Ph.D. degree from Iran University of Science and Technology, Tehran, in 2016, all in Electrical Engineering. Her research interests include power electronics, control of electrical motor drives, supply system of the electric railway (AC and DC), linear motors & MAGLEVs, and analysis of overhead contact systems. She is currently an Assistant Professor with the Department of Railway Engineering and Transportation Planning, University of Isfahan, Isfahan, Iran. Dr. Hamedani was the recipient of the IEEE 11th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC'20) best paper award in 2020.

- Email: p.hamedani@eng.ui.ac.ir
- ORCID: 0000-0002-5456-1255
- Web of Science Researcher ID: AAN-2662-2021
- Scopus Author ID: 37118674000
- Homepage: https://engold.ui.ac.ir/~p.hamedani/

Mahmudreza Changizian was born in Khoramabad, Iran, in 1993. He received the B.Sc. degree from the Arak University of Technology, Arak, Iran, in 2015, the M.Sc. degree from the K. N. Toosi University of Technology, Tehran, Iran, in 2017, and the Ph.D. degree from Iran University of Science and Technology (IUST), Tehran, Iran, in 2022, all in the electrical engineering. His research interests include HVdc systems, modeling and control of high-power electronics converter, grid connected converters, motor drive, and renewable energy systems. He is currently an Assistant Professor with the Department of Railway Engineering and Transportation Planning, University of Isfahan, Isfahan, Iran.

- Email: m.changizian@cet.ui.ac.ir
- ORCID: 0000-0002-3296-6788
- Web of Science Researcher ID: GPF-9103-2022
- Scopus Author ID: 57196393409
- Homepage: https://cetold.ui.ac.ir/~m.changizian

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