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A New Constant Switching Frequency Model Predictive Control Method for Grid Connected 5-level ANPC Inverter with Capacitors Sensor-less Voltage Balancing

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# Abstract:

In this paper, a constant switching frequency model predictive control (MPC) method with capacitors voltages self-balancing is proposed for the 5-level active-neutral-point-clamped (5L-ANPC) grid connected inverter. The proposed MPC provides optimum reference voltage for the 5L-ANPC inverter based on minimizing the derivative of defined cost function with respect to the output voltage of the 5L-ANPC inverter. The generated reference voltage by the proposed MPC is applied to a phase shifted pulse width modulation (PS-PWM) method to provide constant switching frequency and sensor-less voltage balancing of the dc-link and flying capacitors of the 5L-ANPC inverter. Hence, the proposed MPC only needs to measure grid current; thus, the complexity of control system and number of required sensors are notably decreased. The proposed MPC is described and simulation and experimental results are provided for the grid connected 5L-ANPC inverter. The provided simulation and experimental results verify the dynamic and steady state performance as well as viability of the proposed constant switching frequency MPC for the grid connected 5L-ANPC inverter.

# SECTION I. Introduction

Providing less distorted and high quality injected current to the grid by renewable and other distributed generation (DG) energy sources necessitate utilizing more efficient, enhanced, and reliable power electronic converters with less emitted electromagnetic interference (EMI) to meet the electromagnetic compatibility (EMC), and harmonic limits mandated by the relevant stringent standards. Hence, to improve the quality of injected current to the power grid, utilizing multilevel converters (MLCs) can be chosen as a promising solution for integration of renewable energy and other DG sources to the power grid [1][2][3][4][5][6]-[7]. Moreover, employing enhanced control techniques and modulation methods in MLCs are highly demanded to improve transient and steady state performance of the MLCs by utilizing less number of required sensors [8][9][10][11][12]-[13][13]. Among various configurations of multilevel converters (MLCs), the 5L-ANPC converter and its derived hybrid configurations are widely utilized in different industrial applications such as static ground power units (SGPUs) for aircraft, medium-voltage variable frequency drives, and integration of renewable energy sources to the power grid [14][15][16]-[17]. It is comprised of eight power switches, two dc-link capacitors, and one flying capacitor (FC). Four of the power switches commutate at low frequency (LF) and the other four power switches operate at high frequency (HF) [18].

Various modulation and control techniques have been presented in the literature to proper operation of the 5L-ANPC converter. The main goals of the presented control methods and switching patterns are voltage balancing of the dc-link and flying capacitors, providing modified harmonic spectrum of the output voltage, and improving the dynamic and steady state performance of the 5L-ANPC converter. In [10], an improved finite control set model predictive controller (FCS-MPC) has been presented for the 5L-ANPC converter. The presented FCS-MPC only requires measuring load current, neutral point and FC voltages to select the proper switching state of the 5L-ANPC converter and voltage balancing of dc-link and flying capacitors. Hence, the number of required sensors for this FCS-MPC is reduced. A model predictive pulse pattern control (MP3C) method has been presented in [13] for the 5L-ANPC based medium-voltage drive to provide faster torque response and improve the current and stator flux quality. The MP3C has been applied to the 5L-ANPC based ABB ACS 2000 general proposed medium voltage drive. However, even though the presented MPC methods provide improved and faster dynamic response, the switching frequency in the presented MP3C and FCS-MPC methods is not constant. Hence, they have sporadic harmonic spectrum at the output which compels practical issues in design of the output filter.

In order to achieve sensor-less voltage balancing of the dc-link capacitors and flying capacitor, and to obtain constant switching frequency at the output voltage of the 5L-ANPC, the phase shifted PWM (PS-PWM) method, the hybrid level shifted carrier PS-PWM (LSC-PS-PWM) method, and the logic equation based switching method have been presented [8], [12], [14]. Hence, the voltage sensors and closed-loop voltage regulators of the dc-link and flying capacitors are eliminated by employing the presented modulation methods in the 5L-ANPC MLC.

In this paper, to achieve improved performance and faster dynamic response, constant switching frequency, and sensorless voltage balancing of the dc-link and flying capacitors at the same time, a constant switching frequency modulator-based MPC method with sensor-less dc-link capacitors and FC voltage balancing is proposed for the 5L-ANPC grid connected inverter. The proposed MPC provides optimum reference voltage for the 5L-ANPC inverter based on minimizing the derivative of defined cost function with respect to the output voltage of the 5L-ANPC inverter. The generated reference voltage by the proposed MPC is applied to the PS-PWM method to provide constant switching frequency and sensor-less voltage balancing of the dc-link and flying capacitors of the 5L-ANPC inverter.

# SECTION II. Constant Switching Frequency Model Predictive Controller with Capacitors Sensor-less Voltage Balancing

## A. The 5L-ANPC Converter Configuration

Fig. 1 depicts the single-phase 5L-ANPC grid connected system. As shown in Fig. 1, the dc-link capacitors are regulated to *E*/2 and the FC is regulated to *E*/4 to generate five-level output voltage. All switching states, charging/discharging state of the dc-link and flying capacitors, as well as output voltage levels are presented in Table I.

[Fig. 1. - 
The single-phase 5L-ANPC grid connected inverter.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235952/abarz1-p6-abarz-large.gif)

**Fig. 1.** The single-phase 5L-ANPC grid connected inverter.

**TABLE I**Switching states of the 5L-ANPC converter.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Switching State | S4 | S3 | S2 | S1 |  |  |  |
|  | 0 | 0 | 0 | 1 | *-E/2* | 1 | ↓ |
|  | 0 | 0 | 0 | 1 | *-E/*4 | ↑ | ↓ |
|  | 0 | 0 | 1 | 0 | *-E/*4 | ↓ | ↓ |
|  | 0 | 0 | 1 | 1 | 0 | - | - |
|  | 1 | 1 | 0 | 0 | 0 | - | - |
|  | 1 | 1 | 0 | 1 | *+E/*4 | ↓ | ↑ |
|  | 1 | 1 | 1 | 0 | *+E/*4 | ↑ | ↑ |
|  | 1 | 1 | 1 | 1 | *+E/*2 | - | ↑ |

As presented in Table I, in the 5L-ANPC converter, by utilizing the possible redundant switching states to generate ± *E*/4 voltage levels, the FC can be regulated to*E*/4 without using any voltage sensor or closed loop voltage regulator.

## B. The Proposed Constant Switching Frequency MPC Method

The general model of the grid connected 5L-ANPC inverter can be determined based on the inverter voltage dynamic equation as follows

(1)

where  and  are the inductance and series resistance of the grid link inductor,  is the injected current to the grid,  is the grid voltage, and  is the 5L-ANPC output voltage. The discrete-time model of  is calculated as follows by using Euler Forward approximation

(2)

where  is the sampling time. Hence, with respect to (1) and (2), the discrete-time predictive algorithm with one step prediction horizon for controlling the injected current to the grid is expressed as

(3)

where  is the predicted value of the injected current to the grid and  is the estimated value of the grid voltage. Regarding the fact that the variation of the grid voltage is negligible in comparison to the sampling frequency, thus . With respect to (1),  is calculated as

(4)

The aim of the proposed MPC is regulating the value of the injected current to the grid (). Hence, the cost function of the proposed MPC is defined as

(5)

where  is the reference value of the injected current to the grid. It is worth mentioning that since the cost function of the proposed MPC consists of only  term, the weighting factor of the cost function is considered as . In contrast to the presented FCS-MPC in [10] in which the cost function is comprised of the reference current, neutral point voltage, and FC voltage, in the proposed MPC, the cost function only consists of the reference current. Hence, the proposed MPC algorithm only needs to measure the injected current to the grid. Moreover, by employing the PS-PWM method in the proposed constant switching frequency MPC, not only is the constant switching frequency obtained, also sensor-less voltage balancing of the dc-link capacitors and FC are achieved. With regards to (3) and (5),

(6)

where  is calculated by (4). In contrast to the FCS-MPC method in which all of the possible switching states and their corresponding voltage vectors are calculated to find the minimum value of the cost function, the proposed MPC algorithm exploits derivative of the defined cost function with respect to the 5L-ANPC inverter output voltage to generate the minimum  to apply it to the proposed modulation method for the 5L-ANPC. Hence, the main aim of the proposed MPC is find the minimum value of the ,

(7)

Hence, the minimum value of  is calculated by . Thus,

(8)

Accordingly, the proposed MPC algorithm is obtained by (3), (4), and (8). The flowchart of the proposed MPC algorithm is presented in Fig. 2. The calculated value of  is given to the suggested PS-PWM method to generate corresponding switching signals for , , , and . Voltage balancing of the dc-link and flying capacitors without using any closed-loop voltage regulator, and constant switching frequency operation of the 5L-ANPC inverter are obtained by applying the suggested PS-PWM modulation method. Furthermore, by utilizing the suggested PS-PWM modulation method, odd multiples of the switching harmonic clusters are eliminated from the output voltage harmonic spectrum. Hence, the first switching harmonic cluster frequency of the output voltage is doubled which leads to halving the value of the grid link inductor.

# SECTION III. Simulation Results

The grid connected 5L-ANPC inverter controlled by the proposed constant switching frequency MPC with sensor-less modulation method has been simulated in MATLAB/Simulink platform. The performance of the proposed constant switching frequency MPC has been evaluated for both cases of injecting the active power to the grid and exchanging the reactive power with the grid. The main parameters of the simulated grid connected 5L-ANPC converter is illustrated in Table II. In addition, the sampling time of the proposed MPC is set to . The schematic diagram of the simulated grid connected 5L-ANPC inverter controlled by the proposed constant switching frequency MPC with sensor-less modulation method is shown in Fig. 3.

[Fig. 2. - 
Flowchart of the proposed constant switching frequency MPC with sensor-less modulation method.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235952/abarz2-p6-abarz-large.gif)

**Fig. 2.** Flowchart of the proposed constant switching frequency MPC with sensor-less modulation method.

[Fig. 3. - 
The grid connected 5L-ANPC inverter controlled by the proposed constant switching frequency MPC with sensor-less modulation method.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235952/abarz3-p6-abarz-large.gif)

**Fig. 3.** The grid connected 5L-ANPC inverter controlled by the proposed constant switching frequency MPC with sensor-less modulation method.

**TABLE II**Parameters of the Simulated and Implemented Grid Connected 5L-ANPC Converter.

|  |  |
| --- | --- |
| Parameters | Value |
| DC-link voltage |  |
| Power Switched | IRFP460 MOSFE |
| DC-link capacitor |  |
| Flying capacitor (FC) |  |
| Grid frequency |  |
| Grid peak voltage |  |
| Grid-link inductor |  |
| Grid-link inductor series resistance |  |
| Switching frequency |  |

Fig. 4 presents the grid voltage, the injected current to the grid multiplied by 20, the 5L-ANPC inverter output voltage, and the voltage of FC during the converter start-up and steady state for the reference injected current of 10A. As shown in Fig. 4, the injected current to the grid is almost sinusoidal and the FC voltage is regulated to its desired value without utilizing any closed-loop voltage regulator. Hence, the five-level output voltage of the 5L-ANPC inverter is obtained.

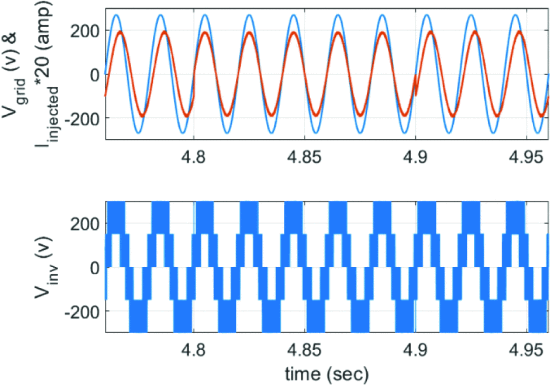
Fig. 5 shows the grid voltage, the injected current to the grid multiplied by 20, and the 5L-ANPC inverter output voltage during step change in the reference injected current from 5A to 10A with unity PF. Moreover, Fig. 6 depicts the grid voltage, the injected current to the grid multiplied by 20, and the 5L-ANPC inverter output voltage during step change in the PF from 0.86 to 1 with the reference injected current of 10A. As presented in Figs. 5 and 6, the proposed constant switching frequency MPC provides improved performance and fast dynamic response for both cases of injecting the active power to the grid and exchanging the reactive power with the grid.

[Fig. 4. - 
The grid voltage, the injected current to the grid multiplied by 20, the 5L-ANPC inverter output voltage, and the voltage of FC during the converter start-up and steady state for the reference injected current of 10A.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235952/abarz4-p6-abarz-large.gif)

**Fig. 4.** The grid voltage, the injected current to the grid multiplied by 20, the 5L-ANPC inverter output voltage, and the voltage of FC during the converter start-up and steady state for the reference injected current of 10A.

[Fig. 5. - 
The grid voltage, the injected current to the grid multiplied by 20, and the 5L-ANPC inverter output voltage during step change in the reference injected current from 5A to 10A with unity PF.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235952/abarz5-p6-abarz-large.gif)

**Fig. 5.** The grid voltage, the injected current to the grid multiplied by 20, and the 5L-ANPC inverter output voltage during step change in the reference injected current from 5A to 10A with unity PF.



**Fig. 6.** The grid voltage, the injected current to the grid multiplied by 20, and the 5L-ANPC inverter output voltage during step change in the PF from 0.86 to 1 with the reference injected current of 10A.

[Fig. 7. - 
The FFT analysis of the injected current to the grid and the FFT analysis of the 5L-ANPC output voltage.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235952/abarz7-p6-abarz-large.gif)

**Fig. 7.** The FFT analysis of the injected current to the grid and the FFT analysis of the 5L-ANPC output voltage.

Fig. 7 depicts the FFT analysis of the injected current to the grid and the FFT analysis of the 5L-ANPC output voltage. As shown in Fig. 7, constant switching frequency operation of the 5L-ANPC inverter is obtained by employing the proposed MPC method. Moreover, the first switching harmonic cluster of the output voltage is shifted to *f*1*st*–*Harmonic* = 20*kHz* whereas the switching frequency is set to *fSW* = 10*kHz* . Hence, the utilized PS-PWM method cancels out the odd multiples of the switching frequency from the output voltage of the 5L-ANPC inverter, and the output voltage frequency spectrum is improved.

# SECTION IV. Experimental Results

The grid connected 5L-ANPC inverter controlled by the proposed constant switching frequency MPC method has been implemented. The proposed controller has been implemented in Texas Instruments TMS320f28335 digital signal controller (DSC) and the injected grid current is measured by LEM LA55-P current sensor. The parameters of the implemented grid connected 5L-ANPC inverter is presented in Table II.

Fig. 8 presents the output voltage of the 5L-ANPC inverter and the injected current to the grid for the reference injected current of 10A. As shown in Fig. 8, the output voltage of the 5L-ANPC inverter has five levels and the injected current to the grid is approximately sinusoidal. The five-level symmetrical output voltage of the 5L-ANPC converter verifies sensor-less voltage balancing of the dc-link capacitors and FC by applying the PS-PWM modulation method. Moreover, Fig. 9 depicts the output voltage of the 5L-ANPC inverter and its FFT analysis. As shown in Fig. 9, the 5L-ANPC inverter operates at constant switching frequency, and though the switching frequency of the 5L-ANPC inverter is *fSW* = 10*kHz* , the first switching harmonic cluster frequency is shifted to around *f*1*st*–*Harmonic* = 20*kHz* . Hence, the odd multiples of the switching frequency are canceled out at the output voltage of the 5L-ANPC inverter. Fig. 10 depicts the FC voltage of the grid-connected 5L-ANPC inverter during the converter start-up. As shown in Fig. 10, the FC voltage is automatically regulated to its desired value which is *E*/4 = 150*V* in about 300*ms* . To evaluate the dynamic performance of the proposed constant switching frequency MPC method, the 5L-ANPC inverter output voltage and the injected current to the grid during step change in the reference injected current from 10A to 5A is presented in Fig. 11. As illustrated in Fig. 11, the proposed constant switching frequency MPC provides very fast response and improved dynamic performance for the grid connected 5L-ANPC inverter.

The match and similarity between the experimental and simulation results verify the feasibility and viability, as well as the dynamic and steady state performance of the proposed constant switching frequency MPC method with sensor-less voltage balancing of the dc-link and flying capacitors.

[Fig. 8. - 
The 5L-ANPC output voltage (Ch1: 200 volt/div), and the injected current to the grid (Ch2: 10 amp/div; current sensor: 100 mv/amp).
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235952/abarz8-p6-abarz-large.gif)

**Fig. 8.** The 5L-ANPC output voltage (Ch1: 200 volt/div), and the injected current to the grid (Ch2: 10 amp/div; current sensor: 100 mv/amp).

[Fig. 9. - 
The 5L-ANPC output voltage (Ch1: 200 volt/div), and its FFT analysis (Math: vertical: 20 volt/div; horizontal: 5 kHz/div).
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235952/abarz9-p6-abarz-large.gif)

**Fig. 9.** The 5L-ANPC output voltage (Ch1: 200 volt/div), and its FFT analysis (Math: vertical: 20 volt/div; horizontal: 5 kHz/div).

[Fig. 10. - 
The FC voltage of the 5L-ANPC during inverter start-up (Ch1: 40 volt/div).
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235952/abarz10-p6-abarz-large.gif)

**Fig. 10.** The FC voltage of the 5L-ANPC during inverter start-up (Ch1: 40 volt/div).

[Fig. 11. - 
The 5L-ANPC output voltage (Ch1: 200 volt/div), and the injected current to the grid (Ch2: 10 amp/div; current sensor: 100 mv/amp) during step change in the reference injected current from 10A to 5A.
](https://ieeexplore.ieee.org/mediastore_new/IEEE/content/media/9235288/9235325/9235952/abarz11-p6-abarz-large.gif)

**Fig. 11.** The 5L-ANPC output voltage (Ch1: 200 volt/div), and the injected current to the grid (Ch2: 10 amp/div; current sensor: 100 mv/amp) during step change in the reference injected current from 10A to 5A.

# SECTION V. Conclusion

In this paper, the constant switching frequency MPC method with sensor-less dc-link capacitors and FC voltages balancing was proposed for the grid connected 5L-ANPC inverter. Only measuring the injected current to the grid is required in the proposed MPC method. The proposed MPC provides optimum reference voltage for the 5L-ANPC inverter based on minimizing the derivative of defined cost function with respect to the output voltage of the 5L-ANPC inverter. The generated reference voltage by the proposed MPC is given to the PS-PWM modulation method to provide constant switching frequency and sensor-less voltage balancing of the dc-link and flying capacitors of the 5L-ANPC inverter. Thus, the complexity of control system and number of required sensors were notably reduced. The proposed MPC was described and simulation and experimental results were provided for the grid connected 5L-ANPC inverter. The simulation and experimental results verified the dynamic and steady state performance as well as the viability of the proposed sensor-less constant frequency MPC for the grid connected 5L-ANPC inverter.

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