

Finite Control Set Model Predictive Control of Cascaded H-Bridge Multilevel Inverter with LC Filter

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[Received on: 11-09-2020 Accepted on: 02-11-2020 Published on: 08-12-2020]

Abstract— A cascaded H-bridge (CHB) multilevel inverter (MLI) is presented in this paper with finite control set model predictive controller (FCS-MPC). MPC predicts the future state of the system using past states and mathematical model of the system. A optimization problem is solved to select the best predicted state and is applied to power circuit for predefined sample time. The presented configuration generates a seven level AC voltage which is passed to unknown load through an LC filter. The aim of this research is to provide a DC-AC converter with good power quality and low harmonic distortions. The proposed topology and controller is theoretically defined, simulated in MATLAB SIMULINK and results are analyzed.

Index Terms— Cascaded H-bridge (CHB), finite control set (FCS), model predictive control (MPC), multilevel inverter (MLI)

I. INTRODUCTION

Power electronic converters have diversified the converter technologies in ways one can think. Nowadays, multilevel converters have been widely preferred in commercial choices, such as; renewable energy conversion, medium to high power conversion applications, industrial motor drives transmission systems and active power filters [1]. Presently, the multilevel inverters (MLI) have three well-recognized topologies namely: Neutral Point Clamped (NPC), Flying Capacitors (FCs) and Cascade H-Bridge (CHB) [2]. Among other topologies, CHB has been raised fascinatingly because of its higher modularity, which enables converter to gain high current and voltage while using semiconductor device of medium voltage. In [3-4] the authors have presented the undertaking research on enhancing the control and modulation techniques. This paper mainly deals with the single phase CHB type inverter topology, which is made up of three cells connected together in series, and each cell has separate DC link with equal voltage.

The conventional methods for control and modulation of CHB MLIs use linear control (such as PID), pulse with modulation (PWM) [5] and space vector modulation [6]. From [7-9] other low switching frequency modulation approaches are discussed.

In recent times, for the control of power electronic converters, many new control techniques have been explored. Among others, the Model Predictive Control (MPC) has been emerged to be applicable for the control of power invertors because of its numerous advantages: easy insertion of nonlinearities, effective fast dynamic response and flexibility to add other system requirements in the controller [10-12]. In Fig. 1, consider a MPC model with its certain equation, a cost function is implemented that predicts the future behavior with respect to time. MPC solves an optimization problem where a series of future operations is accomplished by reducing the cost function. The first element of series with lowest cost function is applied, and process is repeated for every sample interval.

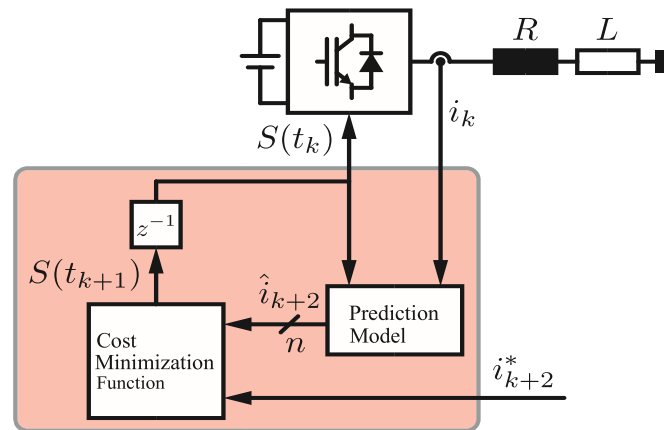


Fig. 1. Basic MPC block diagram [13]

The MPC strategies pertaining to power electronic converters have been classified in two main and other sub-categories shown in Fig. 2 [13-15]. In this paper, Finite Control Set MPC (FCS-MPC) approach is presented and applied on CHB-MLI. The FCS-MPC approach is effective in limiting the number of inverter switching states in order to fix the optimization problem. A time discrete mathematical model of system is employed to predicted future behavior of the system for each permissible actuation series up to the sample time of prediction. Output switching action which results in minimum cost function is applied in next sampling time. FCS-MPC main advantage to directly control the action of the converter without needing a modulation stage.

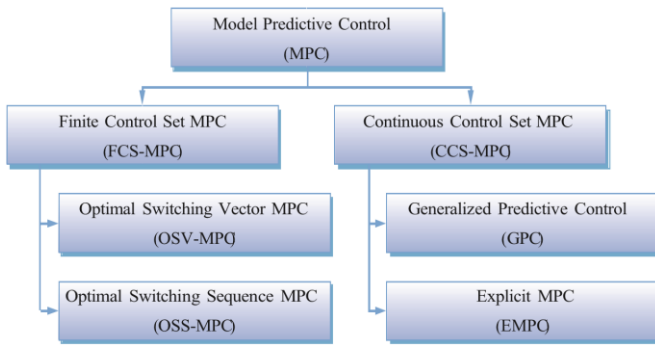


Fig. 2. MPC classification for converters and drives [13]

This paper presents, CHB-MLI which converts DC-AC at seven different levels and FCS-MPC is applied to control the dynamic behavior of CHB-MLI. The CHB-MLI is discussed in section II, while section III presents detail of FCS-MPC including steady state analysis and flow chart etc.

II. CASCADED H-BRIDGE MLI MODEL

Single phase CHB presented in this paper is shown in Fig. 1. It is made up of 3 cells connected together in series and each cell has 4 number of switches with a separate DC source V_{DC} . All cells are capable of producing three levels, V_{DC} , 0, and $-V_{DC}$. The relationship between cells and number of voltage levels produced by single phase CHB is given by

$$N = 2Cn + 1 \tag{1}$$

Where N is the number voltage levels produced and Cn is the number of cells in CHB. Plugging in value of C as 3 gives us number of voltage levels of 7.

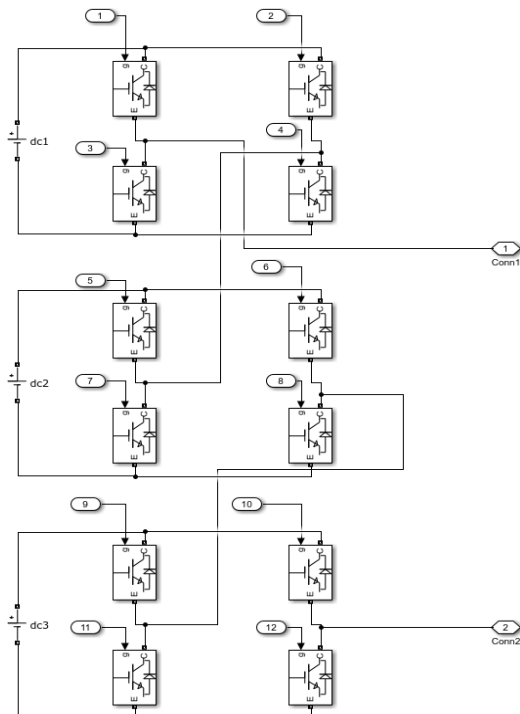


Fig. 1. CHB topology for seven levels

A Controller applies gate signals to all switches to generate required seven voltages. In a practical circuit, care must be taken in turn off and turn on times of switches to prevent circulating currents. Switches should turn on and turn off faster than switching frequency. Table I gives switching table for desired voltage levels for topology in Fig. 1.

TABLE I: Switching table

Switch State (ON or OFF)												Voltage Amplitude
S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	S ₇	S ₈	S ₉	S ₁₀	S ₁₁	S ₁₂	
ON	OFF	OFF	ON	OFF	OFF	ON	ON	OFF	OFF	ON	ON	V_{DC}
ON	OFF	OFF	ON	ON	OFF	OFF	ON	OFF	OFF	ON	ON	$2V_{DC}$
ON	OFF	OFF	ON	ON	OFF	OFF	ON	ON	OFF	OFF	ON	$3V_{DC}$
OFF	OFF	ON	ON	OFF	OFF	ON	ON	OFF	OFF	ON	ON	0
OFF	ON	ON	OFF	OFF	OFF	ON	ON	OFF	OFF	ON	ON	$-V_{DC}$
OFF	ON	ON	OFF	OFF	ON	ON	OFF	OFF	OFF	ON	ON	$-2V_{DC}$
OFF	ON	ON	OFF	OFF	ON	ON	OFF	OFF	ON	ON	OFF	$-3V_{DC}$

Output of CHB is connected to load through an LC filter. General block diagram of circuit is given in Fig. 2. R represents resistive component of inductor. Typically in range of milliohms.

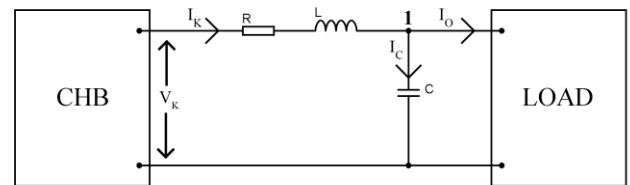


Fig. 2. Block diagram of power circuit

III. MATHEMATICAL MODELING

Load connected is of unknown value and in order to find voltage across voltage, we measure voltage across filter capacitor V_C . To find V_C , KVL law is applied

$$V_K = V_R + V_L + V_C \tag{2}$$

And by expanding terms.

$$V_K = I_K R + L \frac{dI_K}{dt} + V_C \tag{3}$$

Filter inductance dynamics is explained by

$$L \frac{dI_K}{dt} = I_K R + V_C - V_K \quad (4)$$

Similarly capacitance dynamics are explained by applying KCL at node 1.

$$I_C = I_K - I_O \quad (5)$$

$$C \frac{dV_C}{dt} = I_K - I_O \quad (6)$$

A. Discrete-Time Model for Predictive Control

A discrete-time model is required for the MPC to function. To find the discrete-time model for sample time T_s , we approximate the derivative in (4)

$$\frac{dI_K}{dt} = \frac{I_{K+1} - I_K}{T_s} \quad (7)$$

And substitute in (4)

$$I_{K+1} = I_K \left(1 - \frac{RT_s}{L}\right) + \frac{T_s}{L} (V_K - V_C) \quad (8)$$

Following the same procedure for (6) we get

$$V_{C_{K+1}} = V_{C_K} + \frac{T_s}{C} (I_K - I_O) \quad (9)$$

Calculating it at $k+2$ to include I_{K+1}

$$V_{C_{K+2}} = V_{C_{K+1}} + \frac{T_s}{C} (I_{K+1} - I_O) \quad (10)$$

Equations (8), (9), and (10) are utilized to form required predictive control for load voltage.

IV. FINITE CONTROL SET MODEL PREDICTIVE CONTROLLER

FCS-MPC is based on the discrete-time model equations. It is applied on a system where limited number of possible outputs can be generated. For example limited seven output voltage levels in CHB. Possible output states are used in the evaluation of predicted future behavior and an optimizer is used which selects the best output state. Predicted voltage is calculated from (10) from all possible switching states, an optimizer is used which calculates cost function g for each state. Switching state with lowest cost function is selected and the optimum switching state is applied to the CHB switches. This process is repeated for each sampling interval. Fig. 3 shows block diagram for FCS-MPC.

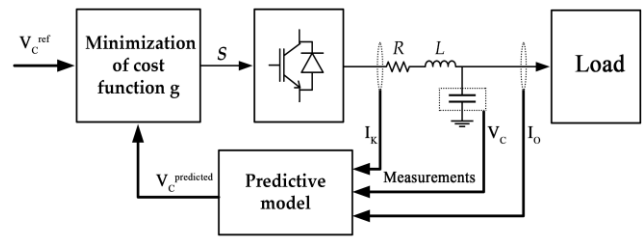


Fig. 3. FCS-MPC block diagram

Measurements are taken for each sample interval, plugged into the discrete-time predictive model. Calculations are done in iterative manner for all possible values of V_K , all seven predicted voltages $V_{C_{k+2}}$ are compared with the sinusoidal reference voltage $V_{C_{ref}}$. This is done by finding the costing function g of all predicted voltages. Cost function is given by

$$g = |V_C^{ref} - V_C^{predicted}| \quad (11)$$

It simply calculates absolute value of error in all seven predicted voltages. Predicted $V_{C_{k+2}}$ with minimum cost function is optimum, its corresponding switching state according to Table 1 is applied to power switches. Flow chart of the algorithm is given in Fig. 4.

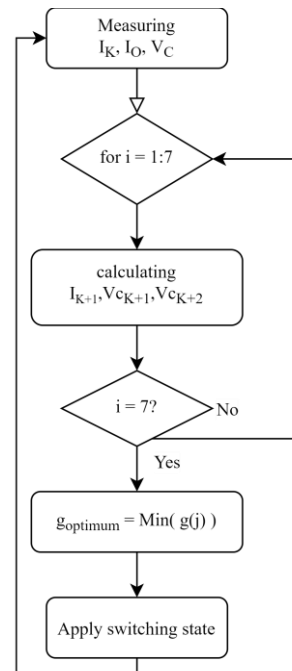


Fig. 4. Algorithm flow chart

V. SIMULATION RESULTS

Simulation is carried out in MATLAB Simulink. A transformer is added on the output of filter to step up the voltage to $220V_{RMS}$. Designed Simulink model is shown in Fig. 5.

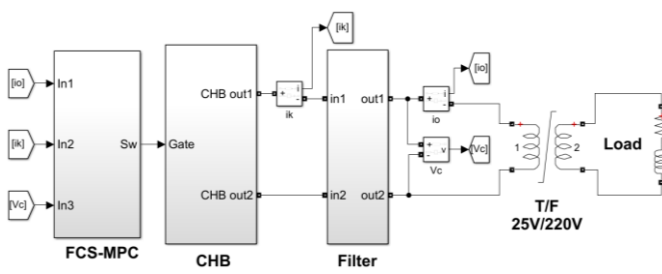


Fig. 5. Simulink model

Parameters for simulations are given in Table II.

TABLE II: Simulation parameters

Variable	Description	Value
V_{DC}	DC source voltage	12V
L_f	Filter inductance	20mH
R_f	Filter resistance	1m Ω
C_f	Filter capacitance	100 μ F
R_L	Load resistance	1k Ω
L_F	Load inductance	500mH
T_s	Sampling Time	100 μ s

A. Steady State Analysis

Simulation is executed and inverter output voltage V_i and output current I_i are shown in Fig. 6 and Fig. 7 respectively. V_i is expected seven level waveform.

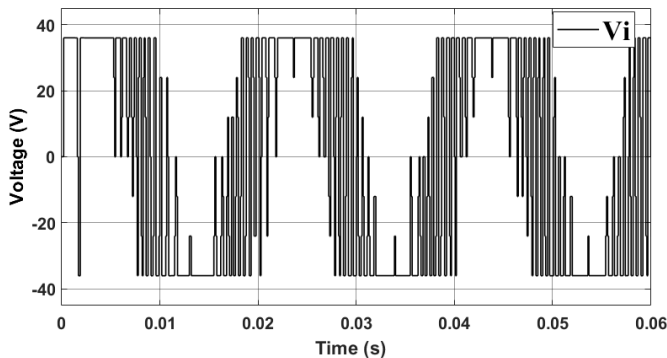


Fig. 6. Inverter output voltage, THD = 75.15%

V_i is not present in any feedback circuit. Priority is given to load voltage V_L and implemented FCS-MPC tries to make load voltage follow a sine wave path. In the starting, there is a small delay due to initial calculation and the fact that predicted voltage is for $k+2$ time, this causes a delay for around 3 time samples. For this reason, V_i is kept at highest voltage by MPC in the starting pulses due to delay, this causes load voltage to increase quickly and follow sine wave trajectory. If its voltage is higher than reference sine wave, MPC applies low voltage or opposite voltage polarity to closely match load voltage with reference. This fact shows in quick switching to different voltage magnitudes. Output current I_i of inverter waveform also contains distortion due to non-sinusoidal voltage but it is corrected by filter.

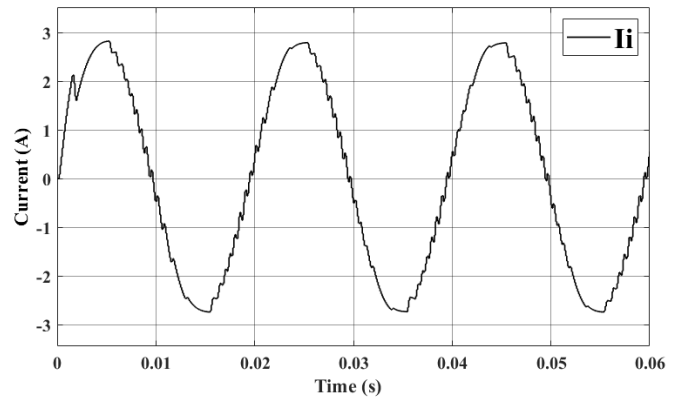


Fig. 7. Inverter output current, THD = 3.89%

Inverter output is passed through filter and transformer before supplying load, load voltage V_L and load current I_L waveforms are given in Fig. 8 And Fig. 9 respectively.

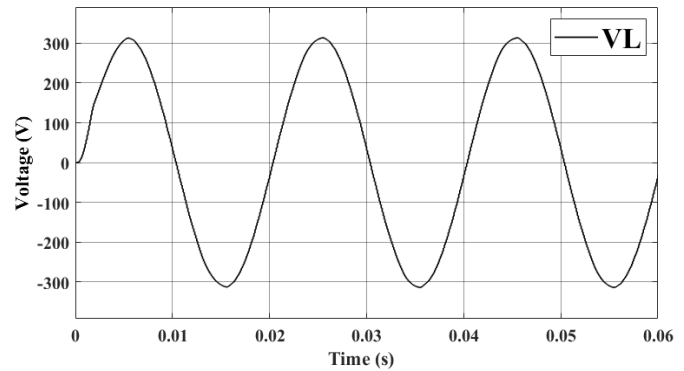


Fig. 8. Load voltage, THD = 0.49%

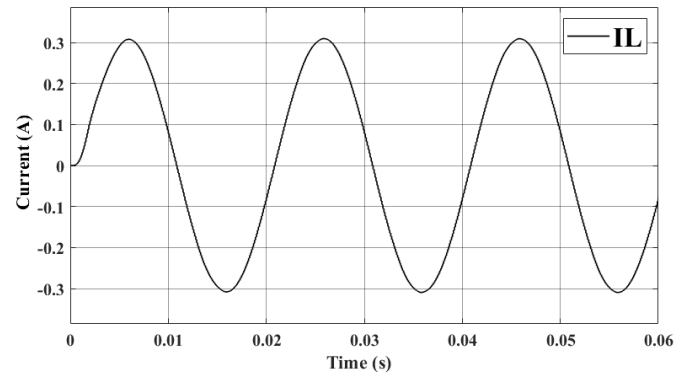


Fig. 9. Load current, THD = 0.35%

B. Transient Analysis

Response to a step change in reference voltage is shown in Fig. 10. Voltage is reduced with some delay due to filter inductance, however it drops more than the reference voltage but quickly follows new reference point. When reference voltage is changed during zero crossing, instead of at peak, new reference is followed without any dips or overshoots.

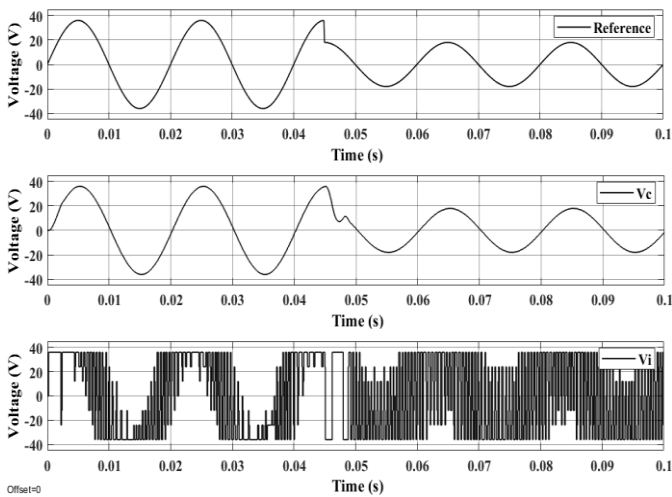


Fig. 10. Inverter response to step change in reference

Phase angle of reference was changed and inverter response waveforms are recorded. Fig. 11 shows that similarly to step change, there is delay in following new set point due to inductance. New reference point is successfully adapted after time of 5ms.

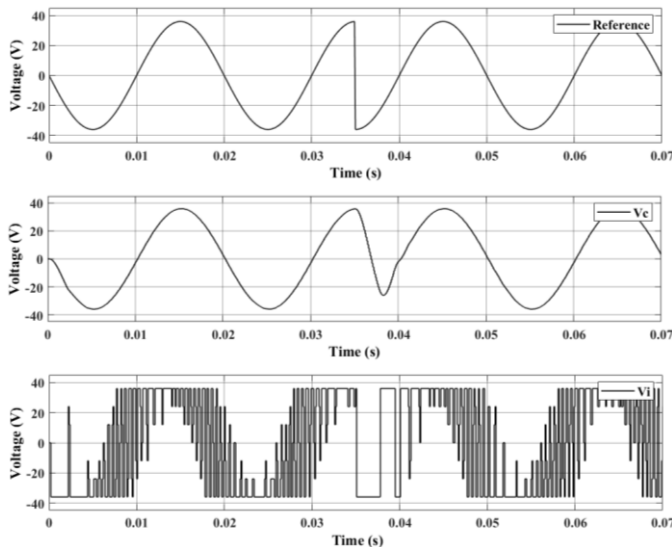


Fig. 10. Inverter response to phase angle change in reference

For final tests, a temporary solid short circuit is simulated on the load side to determine short circuit behavior. Filter and transformer impedances limit short circuit current. After short circuit is removed at $T=2s$ when it is on steady state, voltage and current return to their normal values instantly. Fig. 11 and Fig. 12 show load current and load voltage respectively when temporary short circuit occurs. Constraints on currents can be included for specific value after which it stops selecting any predicted state which causes that value. In case of short circuit, a constraint of current amplitude higher than rated current maybe employed which will effectively stop supplying short circuit. MPCs are deployed using microcontrollers, which could send signals to circuit breaks after current

constraint limited is reached, thus having a protective feature built in MPC.

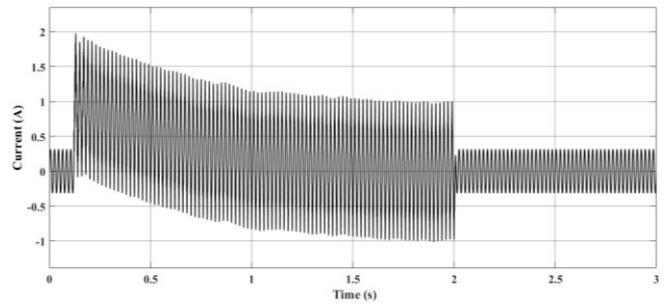


Fig. 11. Load current during temporary short circuit

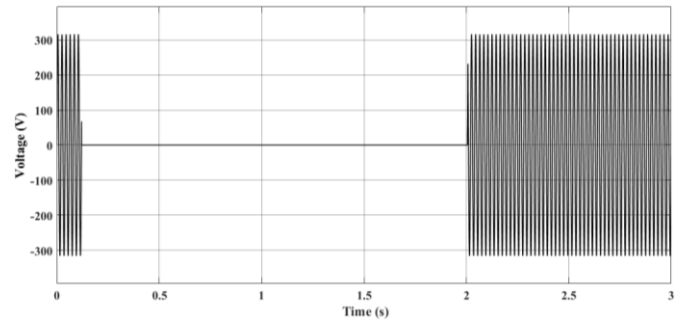


Fig. 12. Load voltage during temporary short circuit

Inverter output voltage V_i in Fig. 13 shows that controller is applying maximum voltage because feedback voltage is zero. Waveform becomes two level of maximum amplitude during short circuit. It recovers fine once short circuit is removed.

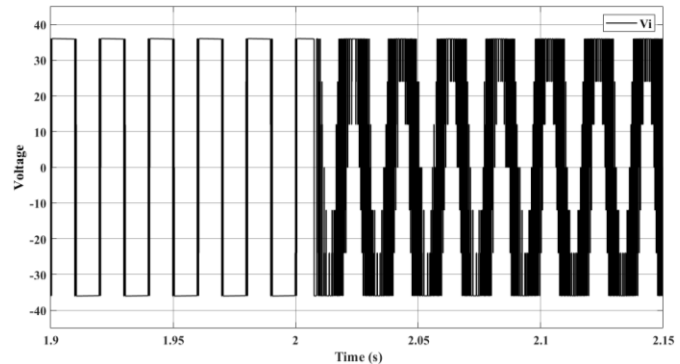


Fig. 13. Inverter output voltage during temporary short circuit

VI. CONCLUSION

In this paper, a CHB inverter of seven levels controlled with FCS-MPC technique is studied and simulated. FCS-MPC predicts future voltage with available finite set of control options. No modulation of gate signals is required and it provides good transient stability and flexibility. It is able to run at lower than designed levels without any change to physical model. No voltage spikes occur and with the help of constraints in optimizer, various control objectives could be achieved, such as limiting high dv/dt values. Multilevel waveform is more closer to sinusoidal waveform which

ultimately results in lower losses in filtering. CHB can be easily be converted into modular design, allowing to add or remove levels of voltages.

Filter capacitor based control is achieved with fast dynamic response. To implement controlling scheme, only discrete-time model of the system is required. There is no tuning required to get satisfactory results. FCS-MPC can be used in various other power converters with different topologies. Controlling technique is simpler than other methods such as PWM techniques where signals are modulated with high frequency carrier. Low distortion and THD is observed on load side of 0.49% in voltage and 0.35% in current, FCS-MPC is a good alternative way for converter control.

Future work can be done to include constraints for protective feature or to achieve different control objectives for different applications. Voltage can be predicted in different way or programming can be optimized for fast execution. Delay compensation can be applied such as done by author in [16].

REFERENCES

- [1] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L. Franquelo, B. Wu, J. Rodr'iguez, M. A. P'erez, and J. Leon, "Recent Advances and Industrial Applications of Multilevel Converters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2553–2580, 2010.
- [2] J. Rodriguez, S. Bernet, B. Wu, J. O. Pontt, and S. Kouro, "Multilevel voltage-source-converter topologies for industrial medium-voltage drives," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 2930–2945, Dec. 2007.
- [3] M. Malinowski, K. Gopakumar, J. Rodr'iguez, and M. A. P'erez, "A Survey on Cascaded Multilevel Inverters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 7, pp. 2197–2206, 2010.
- [4] J. I. Leon, K. Kouro, L. G. Franquelo, J. Rodriguez, and B. Wu, "The Essential Role and the Continuous Evolution of Modulation Techniques for Voltage-Source Inverters in the Past, Present, and Future Power Electronics," *IEEE Trans. Ind. Electron.*, vol. 63, no. 5, pp. 2688–2701, 2016.
- [5] B. P. McGrath and D. G. Holmes, "Multicarrier PWM strategies for multilevel inverters," *IEEE Trans. Ind. Electron.*, vol. 49, no. 4, pp. 858–867, Aug. 2002.
- [6] N. Celanovic and D. Boroyevich, "A fast space-vector modulation algorithm for multilevel three-phase converters," *IEEE Trans. Ind. Appl.*, vol. 37, no. 2, pp. 637–641, Mar./Apr. 2001.
- [7] J. Rodriguez, J. Pontt, P. Correa, P. Cortes, and C. Silva, "A new modulation method to reduce common-mode voltages in multilevel inverters," *IEEE Trans. Ind. Electron.*, vol. 51, no. 4, pp. 834–839, Aug. 2004.
- [8] Y. Liu, H. Hong, and A. Huang, "Real-time calculation of switching angles minimizing THD for multilevel inverters with step modulation," *IEEE Trans. Ind. Electron.*, vol. 56, no. 2, pp. 285–293, Feb. 2009.
- [9] Z. Du, L. M. Tolbert, J. N. Chiasson, and B. Ozpineci, "Reduced switching-frequency active harmonic elimination for multilevel converters," *IEEE Trans. Ind. Electron.*, vol. 55, no. 4, pp. 1761–1770, Apr. 2008.
- [10] J. Rodriguez, J. Pontt, C. A. Silva, P. Correa, P. Lezana, P. Cortes, and U. Ammann, "Predictive current control of a voltage source inverter," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 495–503, Feb. 2007.
- [11] P. Cortes, J. Rodriguez, D. E. Quevedo, and C. Silva, "Predictive current control strategy with imposed load current spectrum," *IEEE Trans. Power Electron.*, vol. 23, no. 2, pp. 612–618, Mar. 2008.
- [12] P. Cortes, M. P. Kazmierkowski, R. M. Kennel, D. E. Quevedo, and J. Rodriguez, "Predictive control in power electronics and drives," *IEEE Trans. Ind. Electron.*, vol. 55, no. 12, pp. 4312–4324, Dec. 2008.
- [13] S. Kouro, P. Cortes, R. Vargas, U. Ammann, and J. Rodriguez, "Model Predictive Control—A Simple and Powerful Method to Control Power Converters," *Industrial Electronics, IEEE Transactions on*, vol. 56, no. 6, pp. 1826–1838, 2009.
- [14] A. Linder, R. Kanchan, R. Kennel, and P. Stolze, *Model-Based Predictive Control of Electric Drives*. Cuvillier Verlag G"ottingen, 2010.
- [15] S. Vazquez, J. Rodriguez, M. Rivera, L. G. Franquelo, and M. Norambuena, "Model Predictive Control for Power Converters and Drives: Advances and Trends," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 2, pp. 935–947, Feb. 2017.
- [16] P. Cortes, J. Rodriguez, C. Silva, and A. Flores, "Delay compensation in model predictive current control of a three-phase inverter," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 2, pp. 1323–1325, 2011.