A Predictive Control Scheme for a Dual Output Indirect Matrix Converter

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***Abstract*—Dual output indirect matrix converter is based on the traditional indirect matrix converter topology, but the conventional six-switch inverter, used in the single-output indirect matrix converter, is replaced by a nine-switch dual output converter. Model Predictive Control (MPC) uses the discrete-time model of the system to predict future value of the controlled variable for all possible control actions and user-defined cost function related to control objectives is solved to find its minimum. The control action which minimizes the cost function is selected and applied to the system for the next time interval. This paper presents a finite control set model predictive control strategy for a single-input dual-output indirect matrix converter.**

I. INTRODUCTION

The Indirect Direct Matrix Converter (IMC) is the two-stage ac-ac power converter and it can convert ac source to ac load without a dc-link capacitor or other storage components. This significantly improves overall system reliability by eliminating failure-prone dc-link electrolytic capacitor. Dual output indirect matrix converter is based on the traditional IMC topology but the conventional six-switch inverter is replaced by a nine-switch inverter. This topology can produce two sets of three phase ac loads since nine-switch inverter is a dual output inverter. Many matrix converter topologies have been proposed, mostly of the single-output type [1], [2]. In many applications, like electric traction and elevators, two or more ac loads need to be controlled independently [3]. Single-output type matrix converters can be used, but multiple converter - one for each output - are required. An alternative is to use multi-output matrix converter, with saving in terms of total number of switches [4], [5]. The dual-output indirect matrix converter, shown in Fig. 1, uses four-quadrant switches in Current Source Rectifier (CSR) stage and has no dc-link capacitor. The rectifier stage is connected to the Nine-Switch Inverter (NSI) stage.

Modulation methods for dual-output indirect matrix converter topology are complicated and using conventional linear control techniques requires tuning of the controller parameters and modulator design. Finite States Model Predictive Control (FS-MPC) is an optimization based control approach that minimizes a cost function to optimize system behavior. MPC uses discrete-time model of the power converters to predict the future behavior of the control variables and solves a cost function to determine optimum control action. The control action that minimizes the cost function is selected and applied to the system for the next time interval [6], [7]. Different control objectives can be introduced in the cost function and controlled simultaneously by solving a single multi-objective cost function [8], [9]. Implementation of model predictive control technique is easy.

In this paper, a model predictive control scheme is proposed for dual-output indirect matrix converter. Different control objectives, like output load current control and minimization of the instantaneous reactive power, are considered and performance of MPC is investigated.

II. SYSTEM MODEL

The rectifier stage includes input filter to eliminate the high frequency component of the input currents and prevent the over voltages. For proper operation the rectifier must provide a positive dc-link voltage to the Nine-Switch Inverter. The rectifier has 9 different switching states and the input voltage is defined as,

$$v_i = \begin{bmatrix} v_{ia} & v_{ib} & v_{ic} \end{bmatrix}^T \quad (1)$$

The relationship between positive dc voltage and input voltages is given by

$$v_{DC} = \begin{bmatrix} S_1 - S_4 & S_2 - S_5 & S_3 - S_6 \end{bmatrix} v_i \quad (2)$$

The input current vector of the rectifier is defined as

$$i_i = \begin{bmatrix} i_{ia} & i_{ib} & i_{ic} \end{bmatrix}^T \quad (3)$$

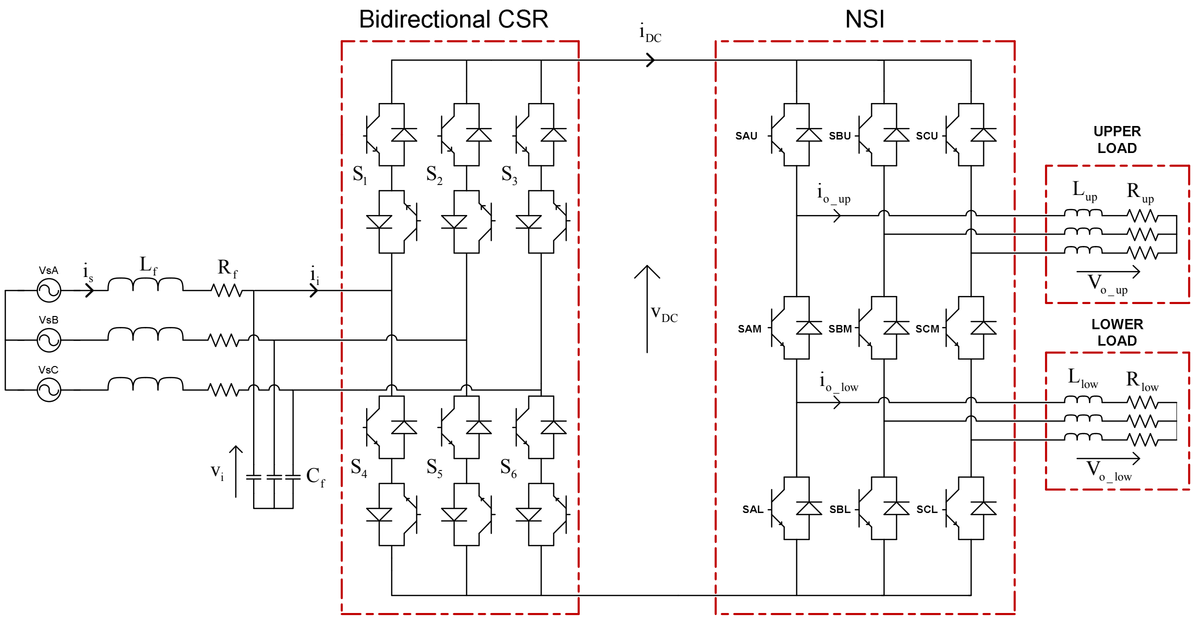

Figure 1. Dual-Output Indirect Matrix Converter Topology

The relationship between the input current and dc-link link current is

$$i_i = \begin{bmatrix} S_1 - S_4 \\ S_2 - S_5 \\ S_3 - S_6 \end{bmatrix} i_{DC} \quad (4)$$

For the NSI topology, each leg has three switches and there are eight different ON-OFF positions. All switches on the same leg cannot be turned on at the same time to avoid DC bus short circuit. Another switching restriction is that at least two switches on the same leg should be on, so that floating of the connected load is avoided. Considering these switching restrictions, each leg can be in three different switch combinations which are called {1, 0, -1} [10]. Possible switch positions are illustrated in Table I with i= A, B and C identifying the inverter leg. The NSI has 27 possible switching states, but, since some of them are redundant, only 15 of these switching states are sufficient to control two ac loads independently [11].

Table I
Switches Positions of Legs

	$S_i = 1$	$S_i = 0$	$S_i = -1$
S_{iU}	ON	OFF	ON
S_{iM}	OFF	ON	ON
S_{iL}	ON	ON	OFF

The instantaneous transfer matrix of upper load T_U is defined as

$$T_U = [S_{AU} \quad S_{BU} \quad S_{CU}] \quad (5)$$

The relationship between output upper load voltage and the dc-link voltage is given by

$$v_{o\_up} = \frac{v_{DC}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} T_U^T \quad (6)$$

The instantaneous transfer matrix of lower load T_L is defined as

$$T_L = [1 - S_{AL} \quad 1 - S_{BL} \quad 1 - S_{CL}] \quad (7)$$

The relationship between output lower load voltage and the dc-link voltage is given by

$$v_{o\_low} = \frac{v_{DC}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} T_L^T \quad (8)$$

The dc-link current is defined as in (9).

$$i_{DC} = T_U \begin{bmatrix} i_{oa\_up} \\ i_{ob\_up} \\ i_{oc\_up} \end{bmatrix} + T_L \begin{bmatrix} i_{oa\_low} \\ i_{ob\_low} \\ i_{oc\_low} \end{bmatrix} \quad (9)$$

In this work, an RL circuit is used as load model for upper load and lower load. Therefore, the continuous-time model of RL load is

$$v_o = Ri_o + L\frac{di_o}{dt} \quad (10)$$

where R is the load resistance and L is the load inductance. The dynamic model of the second order input filter can be expressed as

$$v_s = L_f\frac{di_s}{dt} + R_f i_s + v_i \quad (11)$$

$$i_s = i_i + C_f\frac{dv_i}{dt} \quad (12)$$

III. DISCRETE-TIME PREDICTION MODEL

Model Predictive Control uses a discrete-time model of the system to calculate future value of the controlled quantities. In order to obtain the discrete-time model of the upper load and lower load, the forward Euler approximation is used

$$\frac{di_o}{dt} \approx \frac{i_o(k+1) - i_o(k)}{Ts} \quad (13)$$

Output load current prediction equations are obtained using continuous-time model of the RL circuit (10) and forward Euler approximation (13). Future values of the upper load and lower load currents are given in (14) and (15).

$$i_{o\_up}(k+1) = \frac{Ts}{L_{up}} v_{o\_up}(k) + i_{o\_up}(k)(1 - \frac{R_{up}Ts}{L_{up}}) \quad (14)$$

$$i_{o\_low}(k+1) = \frac{Ts}{L_{low}} v_{o\_low}(k) + i_{o\_low}(k)(1 - \frac{R_{low}Ts}{L_{low}}) \quad (15)$$

The second order input filter can be represented by a state-space model based on (11)-(12) [12]

$$\begin{bmatrix} \dot{v}_i \\ \dot{i}_s \end{bmatrix} = A_c \begin{bmatrix} v_i \\ i_s \end{bmatrix} + B_c \begin{bmatrix} v_s \\ i_i \end{bmatrix} \quad (16)$$

where,

$$A_c = \begin{bmatrix} 0 & \frac{1}{C_f} \\ \frac{-1}{L_f} & \frac{-R_f}{L_f} \end{bmatrix}, \qquad B_c = \begin{bmatrix} 0 & \frac{-1}{C_f} \\ \frac{1}{L_f} & 0 \end{bmatrix} \quad (17)$$

Discrete-time state space model of input filter can be derived using continuous-time model. Considering a sampling time Ts, the discrete-time model of input filter can be expressed as follows,

$$\begin{bmatrix} v_i(k+1) \\ i_s(k+1) \end{bmatrix} = \Phi \begin{bmatrix} v_i(k) \\ i_s(k) \end{bmatrix} + \Gamma \begin{bmatrix} v_s(k) \\ i_i(k) \end{bmatrix} \quad (18)$$

where,

$$\Phi = e^{A_c T_s} \quad , \quad \Gamma = \int_0^{Ts} e^{A_c(Ts-\tau)} B_C d\tau \quad (19)$$

The source current prediction equation is defined as

$$i_s(k+1) = \Phi(2,2)i_s(k) + \Phi(2,1)v_i(k) + \Gamma(2,1)v_s(k) + \Gamma(2,2)i_i(k) \quad (20)$$

Instantaneous reactive power can be calculated using discrete-time model of input filter model. Reactive power is defined as

$$Q(k+1) = v_{s\beta}(k+1)i_{s\alpha}(k+1) - v_{s\alpha}(k+1)i_{s\beta}(k+1) \quad (21)$$

Input reactive power is expressed in α-β frame and Park transformation can be used to calculate real and imaginary parts of the associated vectors.

IV. MPC SCHEME FOR DUAL OUTPUT INDIRECT MATRIX CONVERTER

Model Predictive Control strategy is based on the idea that the model of the system is used to predict the future value of the controlled quantities for each possible switching states, so that appropriate switching state that meets the desired control objectives can be identified. In this work, there are three control objectives: upper load current control, lower load current control and minimization of the instantaneous reactive power. Upper and lower load current tracking terms are defined as in (22) and (23).

$$g_1 = \sqrt{\left|i^*_{o\alpha\_up} - i_{o\alpha\_up}\right|^2 + \left|i^*_{o\beta\_up} - i_{o\beta\_up}\right|^2} \quad (22)$$

$$g_2 = \sqrt{\left|i^*_{o\alpha\_low} - i_{o\alpha\_low}\right|^2 + \left|i^*_{o\beta\_low} - i_{o\beta\_low}\right|^2} \quad (23)$$

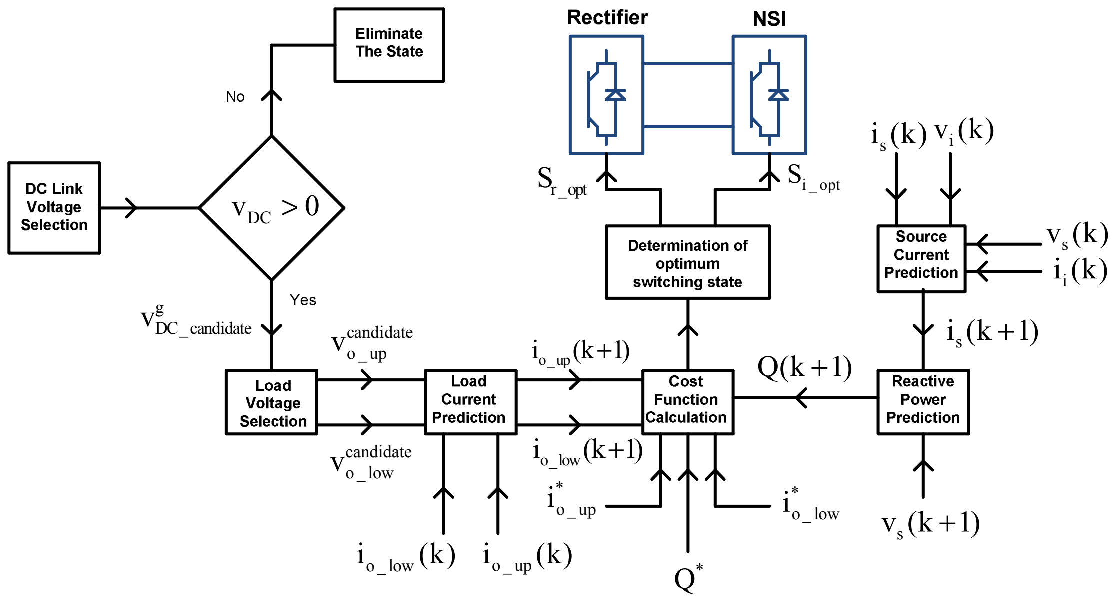

Figure 2. Model Predictive Control Scheme for Dual Output Indirect Matrix Converter

The reactive power term is expressed as

$$g_3 = \left| Q^* - Q \right| \tag{24}$$

For reactive power minimization, reference reactive power Q^* is set to zero. The cost function for this system contains all these three error terms and it is defined as

$$g = Ag_1 + Bg_2 + Cg_3 \tag{25}$$

Predictive control scheme is shown in Fig. 2 and reference values for load currents and reactive power are denoted by superscript "*". Constants A, B and C are the weighting factors. Three phase load currents are calculated in α-β frame and costs for the two ac load current errors are evaluated in this frame. Producing a positive dc-link voltage is necessary for the operation of the NSI stage. The State Elimination process is responsible for selecting rectifier switching states that provide positive dc-link voltage. As a result, only rectifier switching states that produce positive dc-link voltage are used to calculate future load currents.

V. SIMUTATION RESULTS

The Dual Output Indirect Matrix Converter was simulated using MATLAB Simulink. Simulation parameters are listed in Table II. Upper load currents, lower load currents and source current are shown in Fig. 3. In Fig. 3, source voltage for only one phase is shown. According to simulation results, good output load current tracking is obtained. Upper load current THD is 2.37% and lower load current THD is 2.23%. Minimization of the instantaneous reactive power is achieved and source current THD is 21.73%. In order to evaluate dynamic behavior of the predictive control technique, the system step response is shown in Fig. 4. Step response waveform shows that step response time for upper load (system step at t= 0.0271) is 500 µs which corresponds to 25 sampling steps and step response time for the lower load (system step at t=0.0423) is 800 µs which corresponds to 40 system steps. Fig. 4 shows that predictive controller can provide both excellent dynamic and steady-state performance.

Table I
Simulation Parameters

Ts	20 µs
Source Voltage	220 V peak/ 60 Hz
RL load	10Ω / 30mH
Upper Load Current Reference	4 A/ 120 Hz
Lower Load Current Reference	7 A/30 Hz
Rf	0.5 Ω
Lf	145 µH
Cf	32 µF

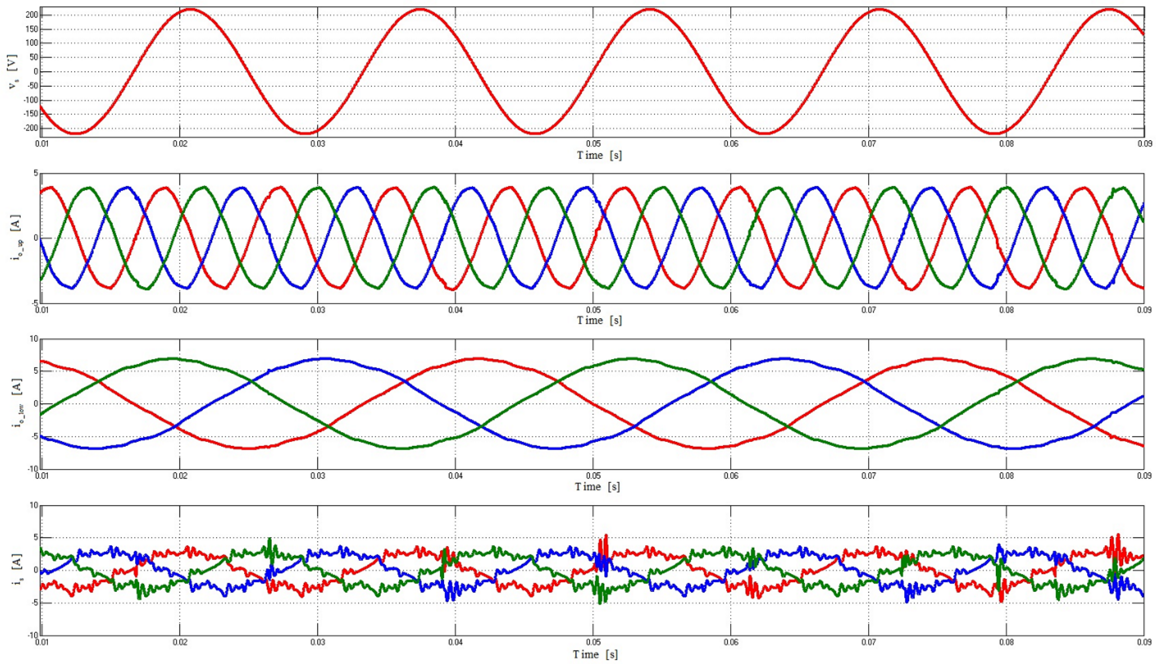

Figure 3. Source Voltage (top), Upper and Lower Load currents (middle), Source current (bottom)

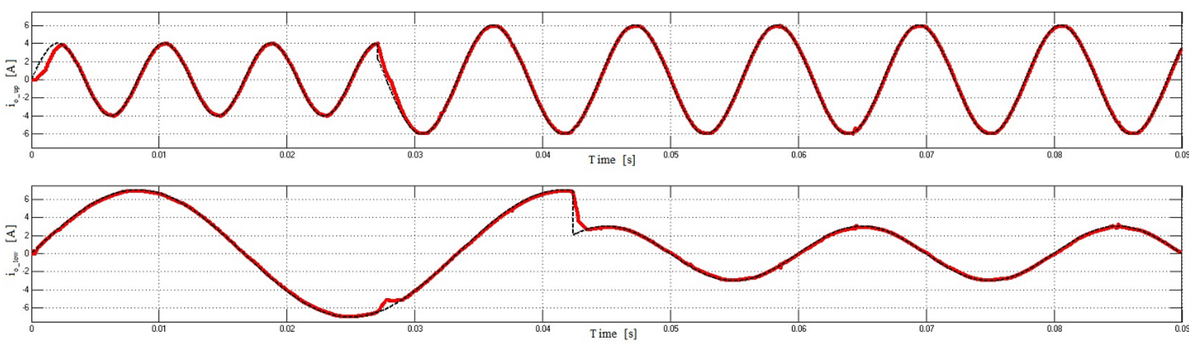

Figure 4. Step response of the predictive controller.

Weighting factors for upper load current tracking and lower load current tracking, A and B, are chosen as 1 and C as 0.0015. This means that upper and lower load current control have the same importance and the weighting factor for the minimization of the instantaneous reactive power is 0.015. In order to further decrease reactive power, the value of C can be increased. However, in this case, predictive controller sacrifices output load current control and controller performance for the output load current tracking is degraded.

Model predictive control technique is able control two ac loads even when their frequencies and magnitudes are different. Two ac loads are controlled independently by solving single multi-objective cost function. The proposed method always provides positive dc-link voltage. Fig. 5 shows that dc-link voltage is always positive. The State Elimination process in the control scheme always provides positive dc-link voltage, which is important for proper operation. The main idea of the state elimination process is that switching combinations of the rectifier stage that generate a negative dc-link voltage are eliminated and future load current for upper load and lower load are calculated using only proper switching combination of the rectifier stage. Fig. 6 shows source current and instantaneous reactive power both with reactive power control and

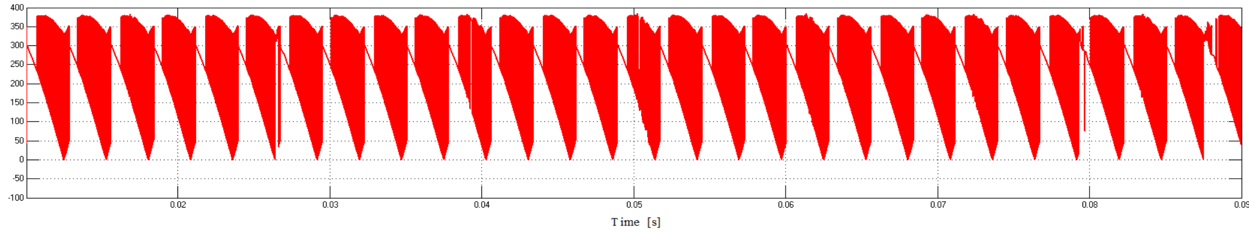

Figure 5. DC-Link Voltage

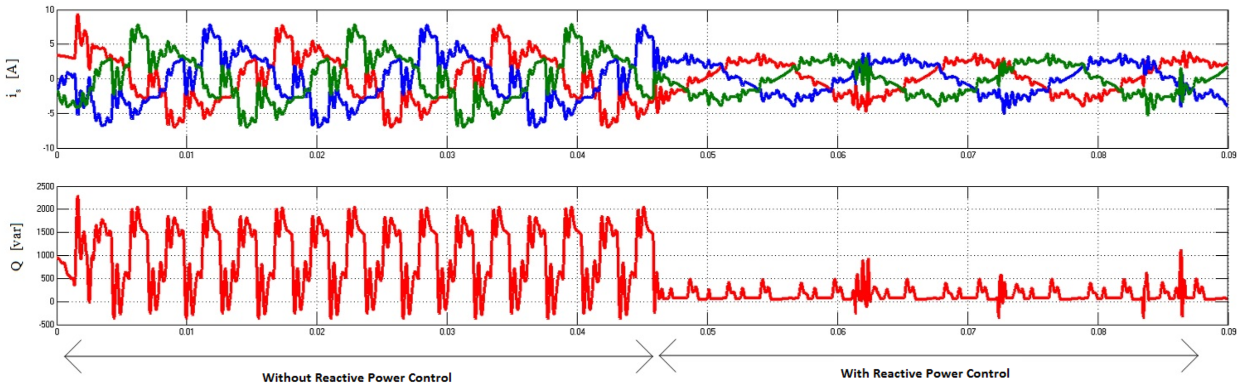

Figure 6. Source Current (top) and Instantaneous Reactive Power (bottom)

without reactive power control. Weighting factor C is initially set at zero so that reactive power is not controlled. Under this condition input current is significantly distorted and input reactive power is large. At time t= 0.046 C is set at 0.015. As a result, input current distortion and reactive power are decreased significantly.

VI. CONCLUSION

In this work, model predictive control of dual output indirect matrix converter is presented. This control scheme uses a discrete-time model of the converter and predicts load current and reactive power to determine the best suited switching combination by solving a multi-objective optimization problem. Model predictive control technique provides fast dynamic response and good steady-state behavior.

Model Predictive Control technique is tested for different control objectives and it performs well under the different conditions. Simulation results show that good system performance was obtained with predictive control scheme in steady state and under transient conditions. The main advantage of the predictive control approach is easy implementation and flexibility. New control objectives can be added in the cost function and controlled simultaneously.

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