

Capacitor-Less D-STATCOM for Reactive Power Compensation

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Abstract— This paper presents a D-STATCOM for reactive power compensation in a distribution system that uses inductive energy storage element connected to the grid via a matrix converter (MC). The MC is controlled using model predictive controller (MPC) technique. The D-STATCOM will provide load compensation without using electrolytic capacitors. Electrolytic capacitors have well-known failure modes. Therefore, reactive power compensators that use a voltage-source inverter (VSI) with electrolytic capacitors as energy storage involve periodic replacement and monitoring constantly. Consequently, this will incur an increase in the cost of the traditional approaches of load compensation significantly. MC system controlled using MPC provides reactive power compensation by controlling the output inductors and the input reactive power. Therefore, the proposed compensator which is based on MC and inductive energy storage has a longer expected service life and more reliability compared with VSI based compensators.

Keywords— *D-STATCOM; Model Predictive Control; Matrix Converter; Power Quality; Reactive Power Compensation*

I. INTRODUCTION

Electrical power systems are complicated networks with hundreds of generators supplying power to thousands of loads interconnected through transmission lines, transformers, and distribution networks. A simplified structure, shown in Fig.1, serves to illustrate the hierarchy in a power system starting from the generating plant, through the transmission system, to the sub-transmission system and down into the distribution system.

As motors from the industrial revolution are replaced with data centers of the digital revolution, the quality of the electrical power becomes a significant concern for both the customer and utility. Reactive power (Q) is a term used for the unreal imaginary power that is supplied or consumed by loads such as capacitors or inductors. Reactive power, called volt-ampere reactive (VAR), is required for the operation of different types of loads. For examples, induction motors, which is heavily used

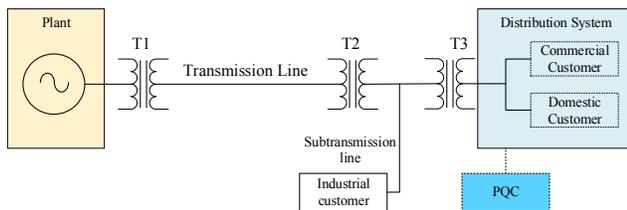


Fig. 1. Typical power system one-line diagram

in many industrial applications, and reactive power is required to produce the revolving magnetic field required to operate the motors.

Reactive power has a number of undesirable effect on electrical power networks. It increases the drawn current for the same load, which will cause an increase in the losses and the maintenance of the power system operation. Also, it will reduce the power transfer capability if not suitably controlled [1-3].

VAR compensation is defined as the management and control of reactive power to enhance ac system performance. Within the literature, there are different types and methodologies used for reactive power compensation. Traditionally, switched capacitors or inductors and rotating synchronous condensers, static VAR compensators (SVCs) using a thyristor-controlled reactors (TCRs), thyristor-switched capacitors (TSCs) and compensation using thyristor-based cycloconverters for reactive power compensation have been used [4-9]. Also, the advent of voltage source inverter (VSI) technology static synchronous compensators (STATCOMs) has been developed. An ac-ac cycloconverters could be used instead of voltage source inverters. However, one of the fundamental disadvantages of cycloconverters is the requirement of a large number of power electronics switches (thyristor), 36 switches when using a three-phase converter. Matrix Converter (MC), is a direct ac-ac power converter that performs as an ac-ac converter [10, 11], is gaining popularity over the other converters for different applications due to the fact that they do not have a DC link capacitors, compact, have simple structure, can operate with unity power factor and allow power to flow between the source and the load, [11, 12]. As all silicon solution, matrix converter lends itself to monolithic integration, which reduces size and cost, improves the reliability over the other discretely built converters.

The power distribution system basic functions are to provide electrical energy to consumers as economical as possible, with a good degree of quality and reliability. The reliability of the system depends primarily on the reliability of the components that make up the system[13].

Electrolytic capacitors are always considered as the weakest device in power electronic systems, due to their well-known failure modes and aging. The main failure modes observed are the degradation of electrical parameters, specifically capacitance and equivalent series resistance (ESR), and the leakage of electrolyte [14-16]. Failure types of DC capacitors are presented in [13, 17]. According to [18, 19], 30% of the failures that occur

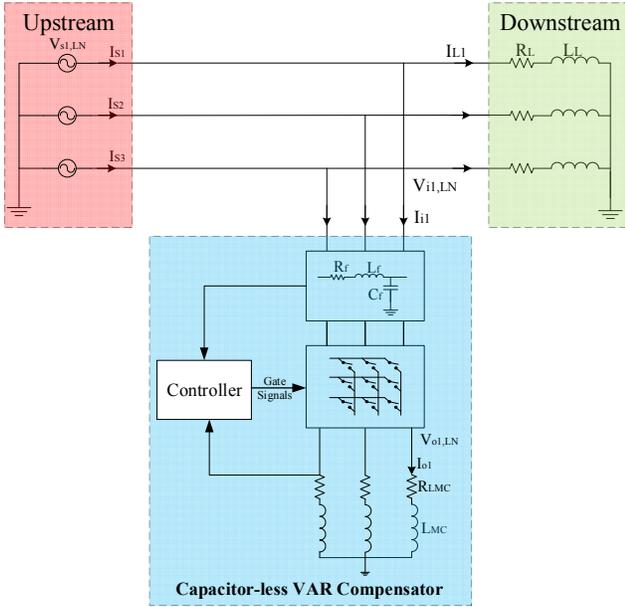


Fig. 2. Capacitor-less D-STATCOM employing MC and inductive energy storage to compensate lagging downstream load

in power electronic systems are mainly because of the use of DC electrolytic capacitors. STATCOM based VSI, with electrolytic DC capacitors, is subjected to this failure rates. Capacitors need to be monitored and maintained regularly [20-22] which will decrease system reliability incur additional cost.

In this paper, D-STATCOM that utilizes inductors which are known to be reliable and robust device instead of electrolytic DC capacitors is proposed. This technique uses direct 3x3 Matrix Converter controlled with MPC. Simulation results of D-STATCOM based matrix converter employed at distribution network will be presented and discussed.

The proposed compensator circuit diagram is illustrated in Fig.2, where the upstream is a lumped model of the supply distribution network, and the downstream is the lumped model of the loads. The MC is controlled using MPC to enable phase inversion between the input and the output currents. This property will enable the converter to supply currents with leading phase angle to the ac network, and absorbing lagging current at the converter output side. Simulation results show that the proposed D-STATCOM can perform all the functions of the conventional compensators without the use of DC capacitors. Thus, in the proposed D-STATCOM:

- The load reactive power is only provided from the output inductors of the MC.
- The use of MPC enables to achieve fast dynamic response
- The use of MPC to control the input reactive power and the output currents of the proposed D-STATCOM can be extended to harmonic power compensation constraints and etc [23, 24].
- The proposed D-STATCOM has the capability of becoming a new reliable and robust FACTS device

II. PRINCIPLES OF MODEL PREDICTIVE CONTROL

With the advancement of modern technology more advanced control techniques have been developed. Some of them are neural networks, fuzzy logic control, sliding mode control, and predictive control (MPC). Among these control techniques, MPC appears to be a very interesting approach to control of power converters [23].

The use of MPC in power electronics applications starts in 1980's [23, 25]. The idea in MPC is to use system model to predict its future behavior at a specific time [23, 26] and then select the appropriate switching that produces a minimum value of cost function and apply it to the converter. The state space model of the variables used can be written as [23]:

$$x(k+1) = Ax(k) + Bu(k) \quad (1)$$

$$y(k) = Cx(k) + Du(k) \quad (2)$$

A cost function J that describe the desired system behavior must be defined, the function considers the reference values, the desired states and the future actuation [23]:

$$J = f(x(k), u(k), \dots, u(k+N)) \quad (3)$$

The cost function must be minimized for a predefined time horizon N , then subjected to the model of the system. The resultant optimal sequence of actuation N will be determined where the controller will apply only the first element of the sequence:

$$u(k) = [1 \ 0 \ \dots \ 0] \arg \min_u J \quad (4)$$

The optimization problem is solved at each sampling time using the new measurements to find a new actuation sequence [26]. The schematic diagram of MPC for power electronic converters is represented in Fig. 3 [26]. The variable $X(k)$ is measured at time k and used in the predictive model to calculate the new value of X at $k+1$, for each switching states of the plants shown in Fig. 3. The predictions then evaluated and the switching state S that corresponds to the minimum cost function is selected and sent to converter to be applied. The definition of cost functions is one of the important steps in designing MPC [27]. The general of the cost function is:

$$J = [X^{p_1}(k+1) - X_1^*(k+1)] + \lambda_1 [X^{p_2}(k+1) - X_2^*(k+1)] + \dots + \lambda_n [X^{p_n}(k+1) - X_n^*(k+1)] \quad (5)$$

For 3x3 MC, 27 switching states are available. Accordingly, 27 cost function values are calculated each sampling period and the switching state that minimizes the cost function is chosen and sent to the converter.

III. SYSTEM MODEL

A. System Description

Fig. 2 shows the overall system, it consists of ac supply, inductive load, and the compensator (D-STATCOM). The D-STATCOM consists of 3x3 MC with inductor bank as energy storage element. This compensator is connected to the point of common coupling at the distribution network side. Input filter must be connected at the input side of the MC to reduce the high

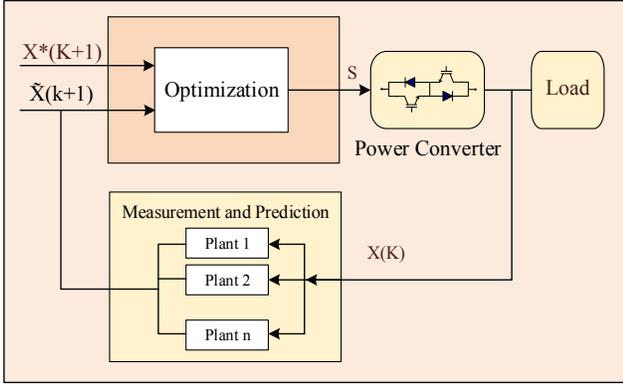


Fig. 3. Schematic diagram of MPC for power converter application.

order harmonics in the input currents. Input filter design is presented in [28].

B. Matrix Converter Model

Matrix Converter is a power converter with an array of controlled bidirectional switches that are controlled to produce variable output voltages at the output side. The output, the input voltages and the modulation matrix \mathbf{H} that relates the output and the input are represented in (6). The detailed working principles are well discussed in [11, 12].

$$\begin{bmatrix} v_{o1,LM} \\ v_{o2,LM} \\ v_{o3,LM} \end{bmatrix} = \mathbf{H} \times \begin{bmatrix} v_{i1,LN} \\ v_{i2,LN} \\ v_{i3,LN} \end{bmatrix} \quad (6)$$

where

$$\mathbf{H} = \mathbf{H}^T = \begin{bmatrix} H_1 & H_2 & H_3 \\ H_2 & H_3 & H_1 \\ H_3 & H_1 & H_2 \end{bmatrix} \quad (7)$$

The symmetric modulation matrix \mathbf{H} is consists of three basic functions \mathbf{H}_1 , \mathbf{H}_2 , and \mathbf{H}_3 :

$$\begin{aligned} H_1 &= \frac{1}{3} \left\{ 1 + 2 \left(\frac{V_o}{V_i} \right) \cos(2\alpha) \right\} \\ H_2 &= \frac{1}{3} \left\{ 1 + 2 \left(\frac{V_o}{V_i} \right) \cos\left(2\alpha - \frac{2\pi}{3}\right) \right\} \\ H_3 &= \frac{1}{3} \left\{ 1 + 2 \left(\frac{V_o}{V_i} \right) \cos\left(2\alpha + \frac{2\pi}{3}\right) \right\} \end{aligned} \quad (8)$$

Assuming a lossless converter, and since the MC has no energy storage elements, then the instantaneous input and output power are equal. The input and output currents relationship can be written using Kirchoff's current law as [29]:

$$\begin{bmatrix} i_{i,1} \\ i_{i,2} \\ i_{i,3} \end{bmatrix} = \mathbf{H}^T \times \begin{bmatrix} i_{o,1} \\ i_{o,2} \\ i_{o,3} \end{bmatrix} \quad (9)$$

where \mathbf{H}^T is the modulation matrix transpose given in (7).

Several papers have investigated the use of MPC for various MC applications [26, 30-36]. The MPC for this MC is based on

the input and output voltages and currents relations defined by (6), (7), (8) and (9). For safe operation, the input terminals of the MC should not short circuit, and also most of the loads have an inductive nature and for this reason, an output phase must never be open circuit.

Modulation methods such as space vector modulation (SVM), use only zero and stationary vectors [37, 38], in this paper all possible 27 switching states are considered for evaluating the cost function. These switching states can be classified as:

- Space vectors with constant amplitude and the variable angle at the source angular frequency: all output phases connected to different input phases.
- Stationary space vectors with a fixed direction and variable amplitude: one output phase connected to a different input phase, and the other two output phases connected to the same input phases.
- Space vectors with zero amplitude: all output phases connected to the same input phases.

C. Load Model

The model of the output inductors that are connected to the output of the MC as an energy storage element must be modeled in order to predict the output current of the MC, the model of the inductors is given by:

$$L_{MC} \frac{di_o(t)}{dt} = v_{oLM}(t) - R_{LMC} i_o(t) \quad (10)$$

The forward Euler method is used to approximate the derivative in (10) at the discrete sample time k :

$$\frac{di_o(t)}{dt} \approx \frac{i_o(k+1) - i_o(k)}{T_s} \quad (11)$$

From (10) and (11), the discrete-time model estimates the current at the next sample ($k+1$):

$$i_o^p(k+1) = \left(1 - \frac{R_{LMC} T_s}{L_{MC}} \right) i_o(k) + \frac{T_s}{L_{MC}} v_{oLN}(k) \quad (12)$$

This model is then evaluated using the output voltage $v_{o,LN}$, produced by each of the possible switching states.

D. Model Predictive Control for Matrix Converters

The proposed MPC scheme is shown in Fig.4. The objectives are to control input reactive power and output currents of the MC. The input reactive power can be expressed by:

$$Q = \text{Im} \left\{ v_{iLN}(t) \cdot \bar{i}_i(t) \right\} \quad (13)$$

where $\bar{i}_i(t)$ is the $i_i(t)$ complex conjugate. The current phase reversal property of the matrix converter indicates that the $i_i(t)$ and $i_o(t)$ are out of phase, this property is proved in [29, 39]. Equation (14) is used to calculate the reactive power.

$$\begin{aligned} Q^p(k+1) &= \text{Im} \left\{ v_{iLN}(k+1) \cdot \bar{i}_i(k+1) \right\} \\ &= v_{iLN\beta}(k+1) i_{i\alpha}(k+1) - v_{iLN\alpha}(k+1) i_{i\beta}(k+1) \end{aligned} \quad (14)$$

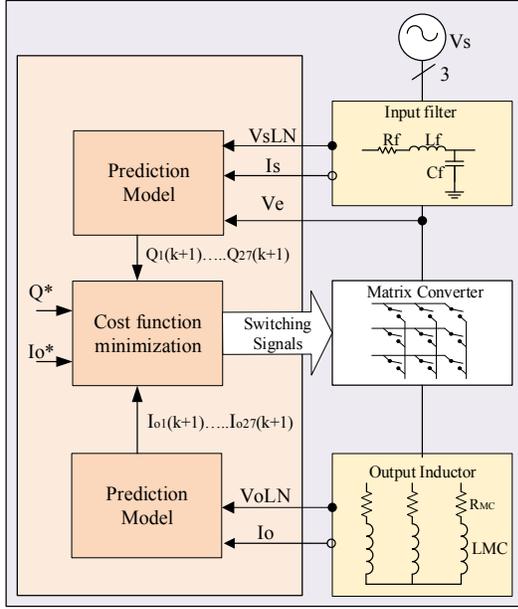


Fig. 4. D-STATCOM control block diagram.

The value of $v_{iLN}(k+1)$ is approximated to be $v_{iLN}(k)$ because the sampling frequency is very small with respect to the line voltage frequency. By keeping in mind current phase reversal property of the matrix converter and (12), the $i_i(t)$ can be calculated. From (5), (12), and (14), the cost function can be described as:

$$J = \left(|i_{o\alpha}^p - i_{o\alpha}^*| + |i_{o\beta}^p - i_{o\beta}^*| \right) + \lambda |Q^p - Q^*| \quad (15)$$

The weight factor λ will define the relative importance of the output current versus input reactive power control. Cost function classification method [23] is used to find the proper of λ . As in Fig. 4 the only parameter that needs tuning is λ . It can be seen from (15) that the output current and the input reactive power needs to be compared with the reference values, and the both of them will evaluate the system behavior for each weight factor.

Fig.5 presents the detailed MPC algorithm for D-STATCOM control. This algorithm starts with the measurements of input and output voltages and currents, and then perform the prediction and calculate the cost function J . The next step is the optimization step where the selection of the minimum cost function and the associated switching state to it. The last step is to apply the selected switching state to the converter.

IV. RESULTS

In this section, the performance of proposed capacitor-Less static VAR compensator based MC will be verified using MATLAB/Simulink tool to model and simulate the system. The D-STATCOM is connected in shunt with the system. Initially, Fig. 6 shows the supply (upstream) voltage and currents waveforms, as the load connected to the supply is an inductive load with 0.85 p.f, the input current is lagging the voltage. At $t=0.1s$, the D-STATCOM is connected to the system to compensate for the load reactive power and it can be seen from the figure that the D-STATCOM was able to compensate for the reactive power and keep the supply voltage and current in phase.

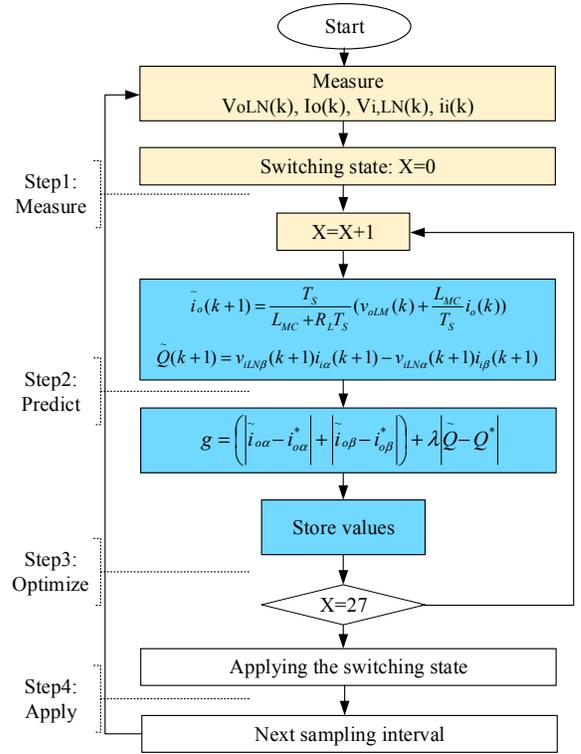


Fig. 5. MPC algorithm of matrix converter. [39]

TABLE I. SYSTEM PARAMETERS

PARAMETERS	VALUE
Grid voltage (Line to neutral) VLN,rms	240 V
Grid frequency (ω)	$2\pi*50$ rad/s
Load Reactive Power (Three phase) (Q)	1612 VAR
Load Active power (Three phase) (P)	2601 W
Load Power Factor (p.f)	0.85
Load resistance per phase (RL)	48 Ω
Load inductance per phase (LL)	94.7 mH
Matrix Converter output inductance (LMC)	30mH
Sampling time (T_s)	60 μ s
Weight factor (λ)	0.0085
Input filter resistance (Rf)	10 Ω
Input filter inductance (Lf)	1mH
Input filter capacitor (Cf)	21 μ F

The matrix converter is controlled to reverse the phase of the input current relative to the output current so that the inductively loaded MC appears to act as if the circuit was a capacitive VAR compensator. Fig. 7, shows that the input current of the MC is leading the output current by 180° , demonstrating the desired circuit operation. Considering Fig.8, it can be seen that output current tracks the reference very closely. The load reactive power as in Table 1 is 1611 VAR, and as can be seen in Fig. 9 the D-STATCOM was able to compensate for all the reactive power required by the load, and this also shown in Fig.6 where the supply voltage and the currents are in phase.

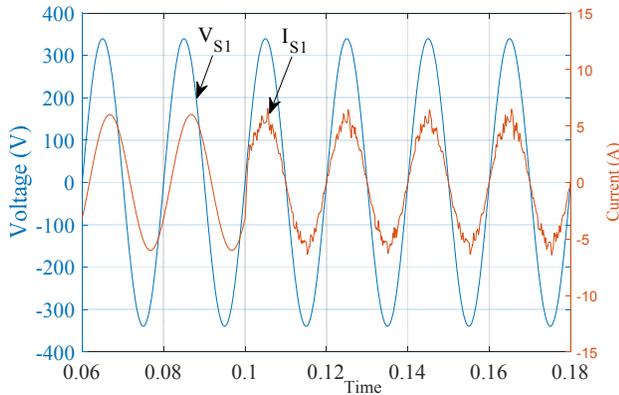


Fig. 6. Supply phase voltage (V_{s1}) and current (I_{s1}) waveforms (phase A).

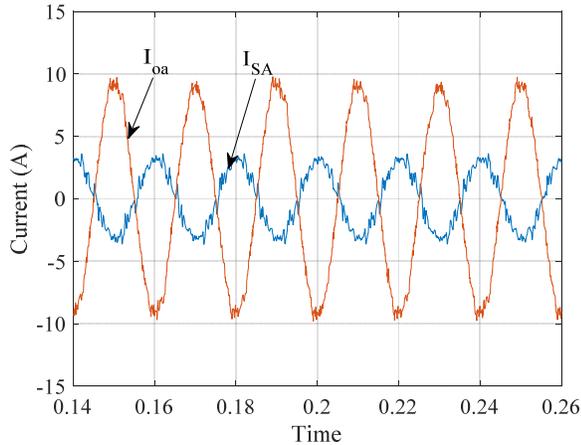


Fig. 7. Phase reversal from output current (I_{oa}) to input current (I_{sa}) of matrix converter.

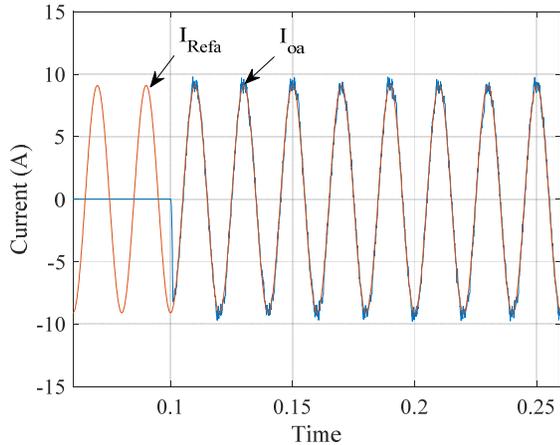


Fig. 8. Output current (I_{oa}) tracking the reference current (I_{ref}) of matrix converter using MPC.

V. CONCLUSION

In this paper, a DSTATCOM capacitor-less approach based matrix converter controlled using MPC is presented. Modeling of 3x3 MC and the MPC operation principles is introduced. The detailed algorithm of the proposed MPC to control DSTATCOM is presented. Simulation results presented in this

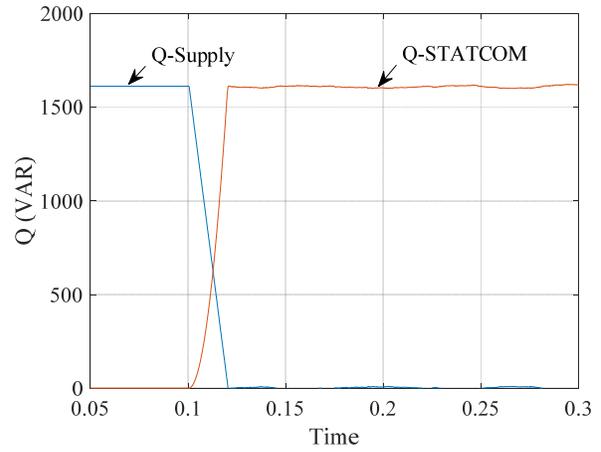


Fig. 9. Reactive power supplied from the ac power system (Q-Supply) and the DSTATCOM (Q-STATCOM).

paper show that good reactive power compensation is achieved using inductors instead of capacitors as an energy storage element. Thus, this technique has the capability of becoming a new FACTS device.

The use of MPC to control the MC for the proposed D-STATCOM can be extended for harmonic compensation techniques. Since the main objective of this paper is validating the model and control of the proposed capacitor-less D-STATCOM, further study in extension such as harmonic compensation is beyond the scope of this paper and can be the emphasis of subsequent papers.

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