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# REACTIVE POWER COMPENSATION USING DSTATCOM IN CAPACITOR-LESS

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**Abstract:** This paper presents a D-STATCOM for reactivepower 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 predictivecontroller (MPC) technique. The D-STATCOM will provide load compensation without using electrolytic capacitors. Electrolytic capacitors have well-known failure modes. Therefore, reactivepower compensators that use a voltage-source inverter (VSI) with electrolytic capacitors as energy storage involve periodic placement 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.

## 1. Introduction:

The concept of Flexible AC transmission system has been proposed in 1995, which is called FACTs. The basic idea of FACTs is installing the power electronic devices at the high-voltage side of the power grid to make the whole system electronically controllable.The advances achieved in high power semiconductor devices and control technology makes the foundation of the development of FACTs. The FACTs devices are able to provide active and reactive power to the power grid rapidly. The power compensation achieved by FACTs devices could adjust the voltage of the whole system and the power flow could be satisfactorilycontrolled. Generally, the FACTs devices and technology could be divided into two generations:

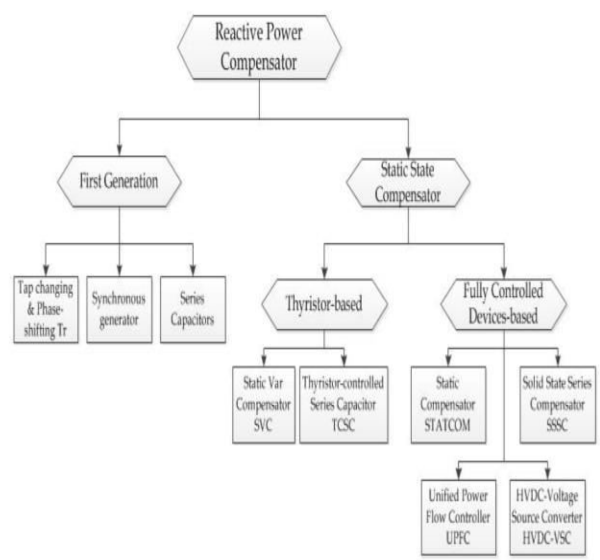


**Figure 1. The category of FACTs devices**

1) Dynamic devices and fixed capacitance devices. This is the first generation of the FACTs devices. In this period, the typical devices are including tap changing and phase changing transformer, synchronous

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generator and series capacitors. Except the series capacitors, which could also be called capacitor bank, others are dynamic devices. These devices are mainly controlled at the generation sideof the power grid and the cost is typically expensive. When talk about the series capacitors, the drawback of this device could hardly be omitted. Since the device is made up of many fixed-capacitance capacitors, it could hardly be controlled to give the real not-fixed capacitance to the grid.

2) Static state compensator. This is the second generation of the FACTs devices. It could be classified into two categories: tyristor-based devices and fully-controlled devices based compensator. The tyristor is calledhalf-controlled device, because it can onlybe controlled to switchonbut notto cut off. Static Var Compensator (SVC) and Thristor-Controlled Series Capacitor (TCSC) are included in this category. The fully controlled devices mainly involve GTO etc. TheStatic Compensator (STATCOM), Solid State Series Compensator (SSSC), Unified Power Flow Controller (UPFC) and HVDC-Voltage Source Converter (HVDC-VSC) are included in this group.

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

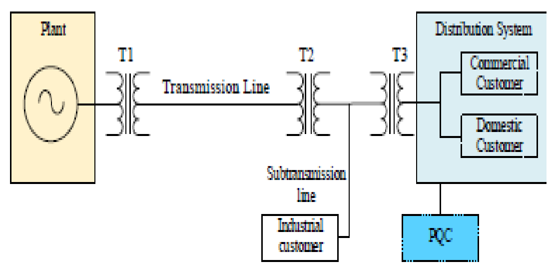


Fig 2: Typical power system one line diagram

in many industrial applications, and reactive power is required to produce the revolving magnetic field required to operate themotors.Reactive power has a number of undesirable effect onelectrical power networks. It increases the drawn current for thesame load, which will cause an increase in the losses and themaintenance of the power system operation. Also, it will reducethe power transfer capability if not suitably controlled [1-3].VAR compensation is defined as the management andcontrol of reactive power to enhance ac system performance.Within the literature, there are different types and methodologiesused for

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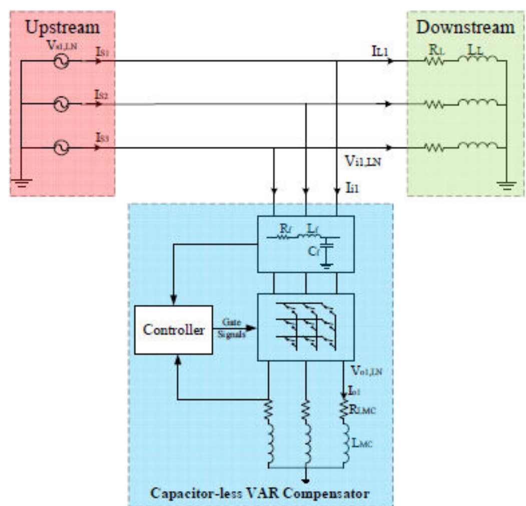
reactive power compensation. Traditionally, switchedcapacitors or inductors and rotating synchronous condensers,static VAR compensators (SVCs) using a thyristor-controlledreactors (TCRs), thyristor-switched capacitors (TSCs) andcompensation using thyristor-based cycloconverters for reactivepower compensation have been used [4-9]. Also, the advent ofvoltage source inverter (VSI) technology static synchronouscompensators (STATCOMs) has been developed. An ac-accycloconverters could be used instead of voltage sourceinverters. However, one of the fundamental disadvantages ofcycloconverters is the requirement of a large number of powerelectronics switches (thyristor), 36 switches when using a threephaseconverter. Matrix Converter (MC), is a direct ac-ac power converter that performs as an ac-ac converter [10, 11], is gainingpopularity over the other converters for different applicationsdue to the fact that they do not have a DC link capacitors,compact, have simple structure, can operate with unity powerfactor and allow power to flow between the source and the load,[11, 12]. As all silicon solution, matrix converter lends itself tomonolithic integration, which reduces size and cost, improvesthe reliability over the other discretely built converters.The power distribution system basic functions are to provideelectrical energy to consumers as economical as possible, with agood degree of quality and reliability. The reliability of thesystem depends primarily on the reliability of the componentsthat make up the system[13].Electrolytic capacitors are always considered as the weakestdevice in power electronic systems, due to their well-knownfailure modes and aging. The main failure modes observed arethe degradation of electrical parameters, specifically capacitanceand equivalent series resistance (ESR), and the leakage ofelectrolyte [14-16]. Failure types of DC capacitors are presentedin [13According to [18, 19], 30% of the failures that occur




in power electronic systems are mainly because of the use of DCelectrolytic capacitors. STATCOM based VSI, with electrolyticDC capacitors, is subjected to this failure rates. Capacitors needto be monitored and maintained regularly [20-22] which willdecreases system reliability incur additional cost.In this paper, D-STATCOM that utilizes inductors which areknown to be reliable and robust device instead of electrolytic DCcapacitors is proposed. This technique uses direct 3x3 MatrixConverter controlled with MPC. Simulation results of DSTATCOMbased matrix converter employed at distributionnetwork will be

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presented and discussed.The proposed compensator circuit diagram is illustrated inFig.2, where the upstream is a lumped model of the supplydistribution network, and the downstream is the lumped modelof the loads. The MC is controlled using MPC to enable phaseinversion between the input and the output currents. Thisproperty will enable the converter to supply currents withleading phase angle to the ac network, and absorbing laggingcurrent at the converter output side. Simulation results show thatthe proposed D-STATCOM can perform all the functions of theconventional compensators without the use of DC capacitors.Thus, in the proposed D-STATCOM:

a. The load reactive power is only provided from the outputinductors of the MC.

b. The use of MPC enables to achieve fast dynamicresponse

c. The use of MPC to control the input reactive power andthe output currents of the proposed D-STATCOM can beextended to harmonic power compensation constraintsand etc [23, 24].d. The proposed D-STATCOM has the capability ofbecoming a new reliable and robust FACTS device

## 2.PRINCIPLES OF MODEL PREDICTIVE CONTROL

With the advancement of modern technology more advancedcontrol techniques have been developed. Some of them areneural networks, fuzzy logic control, sliding mode control, andpredictive control (MPC). Among these control techniques,MPC appears to be a very interesting approach to control ofpower converters [23].The use of MPC in power electronics applications starts in1980's [23, 25]. The idea in MPC is to use system model topredict its future behavior at a specific time [23, 26] and thenselect the appropriate switching that produces a minimum valueof cost function and apply it to the converter. The state spacemodel of the variables used can be written as [23]:

$$x(k+1) = A\,x(k) + B\,u(k) \quad (1)$$

$$y(k) = C\,x(k) + D\,u(k) \quad (2)$$

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

The cost function must be minimized for a predefined timehorizon $N$, then subjected to the model of the system. Theresultant optimal sequence of actuation $N$ will be determinedwhere the controller will apply only the first element of thesequence:

The optimization problem is solved at each sampling time usingthe new measurements to find a new actuation sequence [26].The schematic diagram of MPC for power electronic convertersis represented in Fig. 3 [26]. The variable $X(k)$ is measured attime $k$ and used in the predictive model to calculate the newvalue of $X$ at $k$+1, for each switching states of the plants shownin Fig. 3. The predictions then evaluated and the switching stateS that corresponds to the minimum cost function is selected andsent to converter to be applied. The definition of cost functionsis one of the important steps in designing MPC [27]. The generalof the cost function is:

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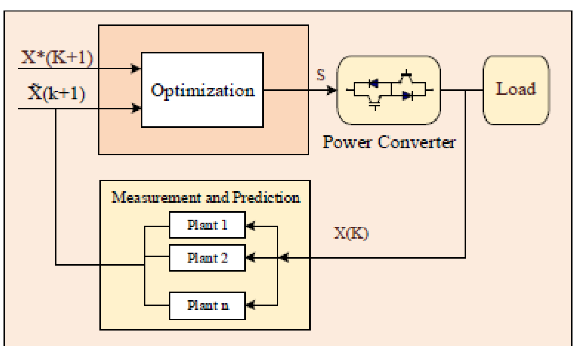
$$J = \left[X^{p_1}(K+1) - X_1^*(K+1)\right] + \lambda_1\left[X^{p_2}(K+1) - X_2^*(K+1)\right] + \ldots + \lambda_n\left[X^{p_n}(K+1) - X_n^*(K+1)\right]$$

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

## 3.SYSTEM MODEL

*A. System Description*

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




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

*B. Matrix Converter Model*

Matrix Converter is a power converter with an array ofcontrolled bidirectional switches that are controlled to producevariable output voltages at the output side. The output, the inputvoltages and the modulation matrix **H** that relates the output andthe input are represented in (6). The detailed working principlesare well discussed in [11, 12]

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

where

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

The symmetric modulation matrix $\boldsymbol{H}$ is consists of three basic functions $\boldsymbol{H1}$ , $\boldsymbol{H2}$ , and $\boldsymbol{H3}$:

$$H_1 = \frac{1}{3}\left(1 + 2\left(\frac{V_o}{V_i}\right)\cos\left(2\omega t\right)\right)$$

$$H_2 = \frac{1}{3}\left(1 + 2\left(\frac{V_o}{V_i}\right)\cos\left(2\omega t - \frac{2\pi}{3}\right)\right)$$

$$H_3 = \frac{1}{3}\left(1 + 2\left(\frac{V_o}{V_i}\right)\cos\left(2\omega t + \frac{2\pi}{3}\right)\right)$$

Assuming a lossless converter, and since the MC has noenergy storage elements, then the instantaneous input and outputpower are equal. The input and output currents relationship canbe written using Kirchhoff's current law as [29]:

$$\begin{bmatrix} i_{i.1} \\ i_{i.2} \\ i_{i.3} \end{bmatrix} = \mathbf{H}^T \times \begin{bmatrix} i_{o.1} \\ i_{o.2} \\ i_{o.3} \end{bmatrix}$$

Several papers have investigated the use of MPC for variousMC 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 theMC should not short circuit, and also most of the loads have aninductive nature and for this

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reason, an output phase must neverbe open circuit.

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

a. Space vectors with constant amplitude and the variableangle at the source angular frequency: all output phasesconnected to different input phases.

b. Stationary space vectors with a fixed direction andvariable amplitude: one output phase connected to adifferent input phase, and the other two output phasesconnected to the same input phases.

c. Space vectors with zero amplitude: all output phasesconnected to the same input phases.

*C. Load Model*

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

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

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

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

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

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

This model is then evaluated using the output voltage *vo,LN*,produced by each of the possible switching states.

*D. Model Predictive Control for Matrix Converters*

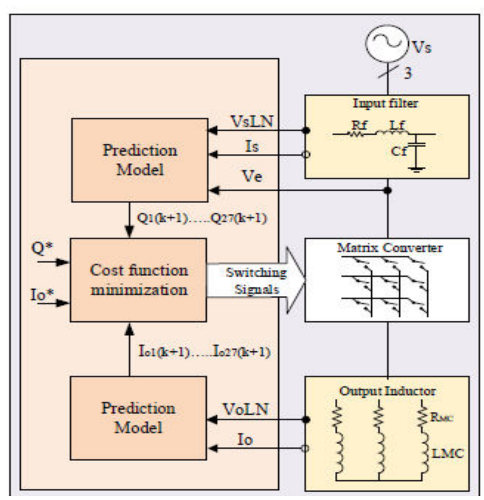
The proposed MPC scheme is shown in Fig.4. The objectivesare to control input reactive power and output currents of theMC. The input reactive power can be expressed by:

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

where *i* (*t*) *i* is the *i* (*t*) *i* complex conjugate. The current phasereversal property of the matrix converter indicates that the *ii(t)*and *io(t)* are out of phase, this property is proved in [29, 39].

Equation (14) is used to calculate the reactive power.

$$Q^p(k+1) = \text{Im}\left\{v_{iLN}(k\ +1).\bar{i}_i(k\ +1)\right\}$$
$$= v_{iLN\beta}(k\ +1\ )i_{i\alpha}(k+1) - v_{iLN\alpha}(k\ +1)i_{i\beta}(k\ +1)$$



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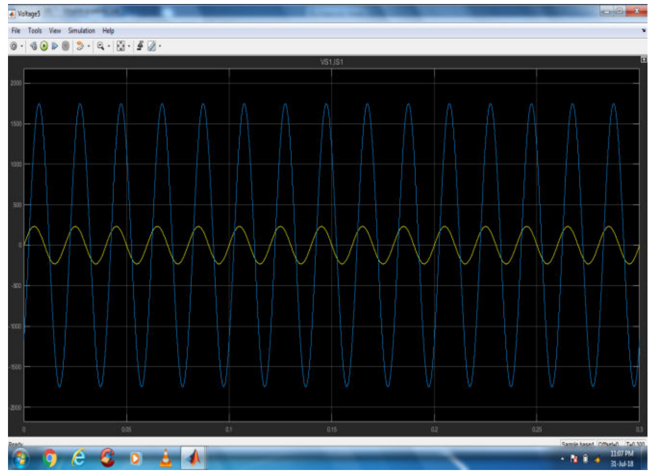
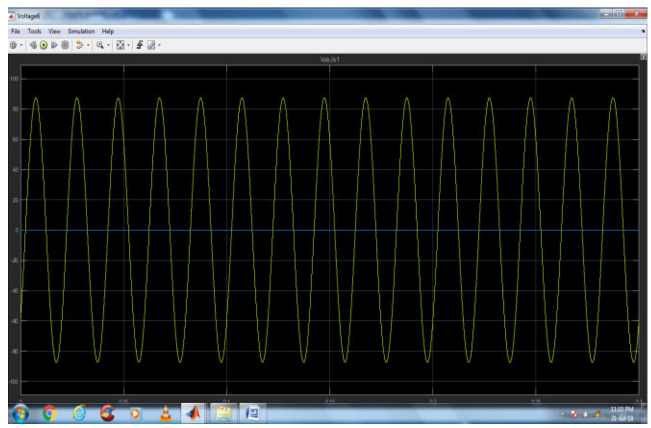
$$J = \left(\left|i^{p}_{o\alpha} - i^{*}_{o\alpha}\right| + \left|i^{p}_{o\beta} - i^{*}_{o\beta}\right|\right) + \lambda\left|Q^{p} - Q^{*}\right|$$

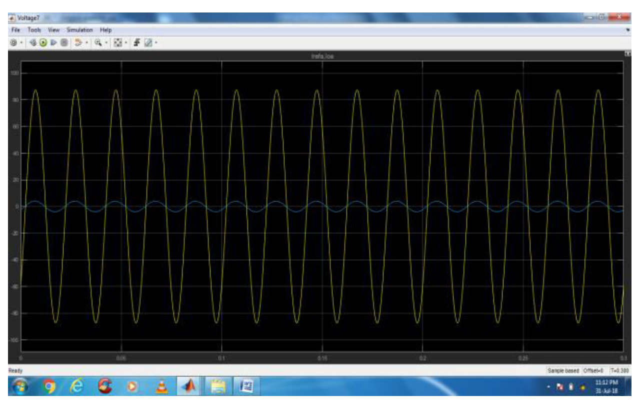
The value of *viLN (k+1)* is approximated to be *viLN (k)* because thesampling frequency is very small with respect to the line voltage frequency. By keeping in mind current phase reversal propertyof the matrix converter and (12), the *ii(t)* can be calculated. From(5), (12), and (14), the cost function can be described as:

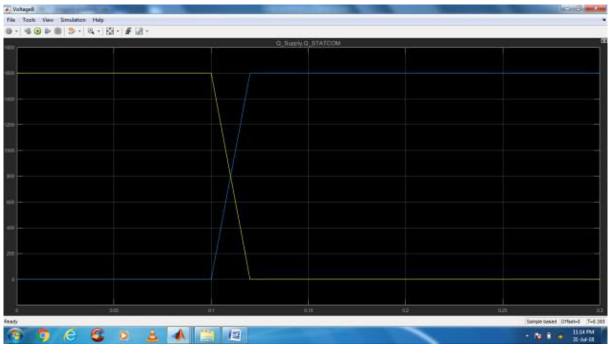
The weight factor $\lambda$ will define the relative importance of the output current versus input reactive power control. Cost functionclassification method [23] is used to find the proper of $\lambda$. As inFig. 4 the only parameter that needs tuning is $\lambda$. It can be seen from (15) that the output current and the input reactive powerneeds to be compared with the reference values, and the both ofthem will evaluate the system behavior for each weight factor.Fig.5 presents the detailed MPC algorithm for DSTATCOMcontrol. This algorithm starts with themeasurements of input and output voltages and currents, andthen perform the prediction and calculate the cost function *J*. Thenext step is the optimization step where the selection of theminimum cost function and the associated switching state to it.The last step is to apply the selected switching state to theconverter.

## 4. SIMULATION RESULTS









## 5. CONCLUSION

In this paper, a DSTATCOM capacitor-less approach based matrix converter controlled using MPC is presented. Modelingof 3x3 MC and the MPC operation principles is introduced. Thedetailed algorithm of the proposed MPC to controlDSTATCOM is presented. Simulation results presented in thispaper show that good reactive power compensation is achievedusing inductors instead of capacitors as an energy storageelement. Thus, this technique has the capability of becoming anew FACTS device.The use of MPC to control the MC for the proposed DSTATCOMcan be extended for harmonic compensationtechniques. Since the main objective of this paper is validatingthe model and control of the proposed capacitor-less DSTATCOM,further study in extension such as harmoniccompensation is beyond the scope of this paper and can be theemphasis of subsequent papers.

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