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Comparative Analysis of Deadbeat Controller and Model Predictive Controller on DSTATCOM for Power Quality Improvement

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Abstract: ***Distribution Static Compensator (DSTATCOM) is a shunt compensation device that is used to solve power quality issues. The control strategy of the DSTATCOM plays an important role in reducing current harmonics and power factor correction. In this paper comparative analysis of two predictive controllers on DSTATCOM are done. Two different predictive control structures i.e. deadbeat and model predictive controller applied to DSTATCOM for power quality improvement are discussed. In deadbeat predictive algorithm, state space model of the system is used to calculate the require reference value of current in order to reach the desired value for load current. In model predictive current control method, a discrete-time model of the system to predict the future current behavior for all the possible voltage vectors generated by the DSTATCOM, and then the vector which minimizes a cost function is selected and applied. These controllers allow DSTATCOM to tackle power quality issues by providing power factor correction, harmonic elimination, load balancing and voltage regulation. MATLAB based simulink model is used to determine the effectiveness of the proposed controllers.***

Keywords: Distribution static compensator (DSTATCOM), Model predictive controller (MPC), power quality (PQ), and Voltage-source inverter

1. Introduction

Power quality is a term that means different things to different people. Institute of Electrical and Electronic Engineers (IEEE) Standard IEEE 1100 defines power quality as “The concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment”. The power quality at the point of coupling (PCC) is regulated by various standards such as IEEE-519 standard [1].Wide use of power electronics devices and sensitive equipment leads to voltage and current waveform distortion.

The FACTs devices are introduced to electrical systems to improve the quality of electrical power [3]. Most widely known custom power devices are DSTATCOM, UPQC, and DVR[4]. Among them DSTATCOM is very well known and can provide cost effective solution for reactive power compensation and load regulation. Distribution Static Compensator (DSTATCOM) is used to rectify various power quality issues. The DSTATCOM is a voltage source converter based custom power device which can perform as a reactive power source in power systems. The DSTATCOM can regulate magnitude of voltage at a particular AC bus, at the Point of Common Coupling (PCC that is the point where it is connected), via generating or absorbing reactive power from the system [9]. In this paper, the application of DSTATCOM to reduce current harmonics and improve power factor is presented.

The internal control of a DSTATCOM plays a very important role in the effective operation of the DSTATCOM .Several control algorithms have been proposed to control the DSTATCOM such as LQ control repetitive control, sliding mode control, and soft computing techniques such as fuzzy ANN, predictive control etc[5]. A classical controllers have been developed by linear controller like P,PI and PID controllers with modulation schemes such as voltage oriented control, direct power control, space vector PWM [7]. There are some drawbacks of these methods follow as tuning of controller is a complex task, mismatch of nonlinear system with linear control, limitation of analog control, computational time of controller [7]. However, by advance technology in the field of computer and digital signal processing, modern techniques have been developed for inverters controlled such fuzzy, neural, adaptive and predictive control. The linear controllers are replaced by neural network trained back propagation algorithm, but this training is done offline. So this NN based control strategy is not adaptive.

The main character of predictive control is that, the model of system is used for prediction of controlled variables and selects the most appropriate control set based on quality function. The classification of model predictive control such as hysteresis based control, trajectory based control, dead beat controller and model based predictive control [8]. In Hysteresis based predictive control the system variables varies between hysteresis bands. The trajectory based is to force the system’s variables onto pre-calculated trajectories. Combination of hysteresis and trajectory based strategies likes direct speed control, sliding mode or direct torque control etc. Most known type of predictive controller use is dead beat controller [12]. The model of the system is used to calculate the required reference value in order to reach the desired input signal. The modulation is operated by comparing the carrier signal to the reference signal. The control for gate signal is generated from the different type of modulation.

A different approach called Model predictive control (MPC) is capable of predicting future output signals based on predicted value of input signals and initial values [8]. A model of the system is considered in order to predict the future behavior of the variables over a time horizon. These predictions are evaluated based on the character of the system and cost or quality function [7]. The sequence that minimizes the cost function is selected to predict the future input signal to the system. There are different kind of MPC such as generalized MPC , MPC with nonlinear state space model , MPC with continuous control set, MPC with finite control set, hybrid model MPC, explicit MPC and nonlinear MPC. As the inverter can be modeled as a system with a finite number of switching state, thus a finite control set MPC can be applied for this system [5].

MPC has many advantages, like fast dynamic response, modulation is not required, easy inclusion of nonlinearities and constraints of the system, and the flexibility to include other system requirements in the controller. Consider inverters with a finite number of states, given by the possible combinations of the state of the switching devices, the MPC optimization problem can be simplified and reduced to the prediction of the behavior of the system for each possible state. Then, each prediction is evaluated using the cost function and the state that minimizes the cost function, is selected. MPC is a different approach that can be successfully applied for the current control in a DSTATCOM.

The control strategy for the DSTATCOM plays an important role in reducing current harmonics and power factor correction. Different controllers like linear, non linear, predictive adaptive etc can be used to improve the power quality. In this paper comparative analysis between predictive controllers are done. Two different predictive control structures i.e. deadbeat and model predictive controller applied to DSTATCOM for power quality improvement are discussed. In deadbeat predictive algorithm, state space model of the system is used to calculate the require reference value of current in order to reach the desired value for load current. In model predictive current control method, a discrete-time model of the system to predict the future current behavior for all the possible voltage vectors generated by the inverter, and then the vector which minimizes a cost function is selected and applied to DSTATCOM. These control strategy allow DSTATCOM to tackle power quality issues by providing power factor correction, harmonic elimination. MATLAB based simulink model is used to compare the effectiveness of the proposed controllers.

2. FCS-MPC Operating Principle

2.1 The Control Strategy

The concept behind model predictive control strategy is that only a finite number of possible switching states can be generated by the inverter. In model predictive controller, a model of the system is used to predict the behavior of the variable for each switching state. Based on the model of the system a cost or quality function is defined, which is used as a solution to optimization problem. These quality functions will evaluate for the predicted value of variables to be controlled. Prediction of future value of input variables is calculated for each possible switching state. The switching state that minimizes quality function is selected.Fig.1 shows the block diagram for model predictive controller.

The principle of the MPC is to generate process inputs (control actions) online, which serve as a solution to practical optimisation problem which is solely dependent on the system model and system measurements. The process measurement acts as the MPC's feedback and or feed forward element. The basic structure of a typical MPC is described through figure 1.

As a solution to power quality issues, appropriate switching pulse should be given to DSTSTCOM. DSTATCOM is a shunt connected voltage source inverter .Determination of an appropriate control action *S(t)* i.e. the gate signal to inverter that ,will drive a generic system variable *x(t)* usually the input current as close to desired reference value $x^*(t)$.Since the control set is finite in number S_i ,with, i=1,..........n. The future reference value $x^*(t_{k+1})$ can be estimated via appropriate extrapolation methods.

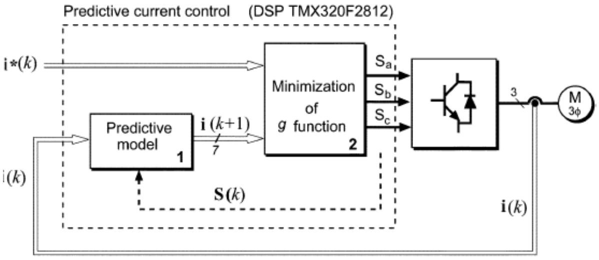

Figure 1: Predictive current control block

A discrete-time model of the load is needed to predict the behavior of the variables using quality function i.e. the load current should be equal to the reference current.
As the inverter can be modeled as a system with a finite number of switching state, thus a finite control set MPC can be applied for DSTACOM [5].

The power quality improvement is performed in the following steps.

1) The value of the reference current $i^*(k)$ is obtained, and load current i(k)is measured.
2) The model of the system is used to predict the value of the load current in the next sampling interval i(k+1) for different voltage vector
3) The quality function g evaluates the error between reference and predicted currents in the next sampling interval. The voltage that minimizes the current error is selected and applied to the load.

By selecting appropriate switching pulse to the inverter eliminate current harmonics and power factor correction can be done. Basic MPC structure is shown in Figure 2.

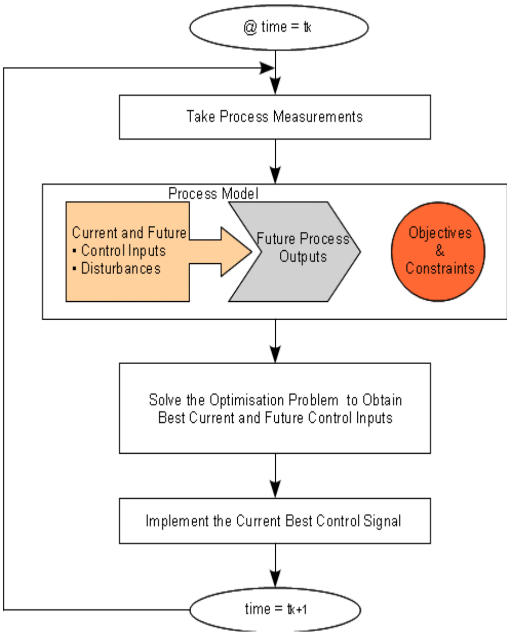

Figure 2: Basic MPC structure

2.2 Quality Function

Quality function is defined to minimize the error between predicted value and the reference value of the quantity to be controlled. For eliminating current harmonics of distribution system load current is measured and its predicted value is calculated. Reference value of load current is calculated using d-q transformation. The quality function is defined as [8],

$$g = \left|i_\alpha{}^* - i_\alpha{}^p\right| + \left|i_\beta{}^* - i_\beta{}^p\right| \quad (1)$$

Where $i_\alpha{}^p$ and $i_\beta{}^p$ are the real and imaginary part of predicted load vector i(k+1),$i_\alpha{}^*$ and $i_\beta{}^*$ are the real and imaginary part of the reference current.

Different control criteria will be expressed in different quality functions. In this work absolute error is used for computation simplicity.

2.3 DSTATCOM Model

The power circuit of the DSTATCOM considered in this work is shown in Fig.4

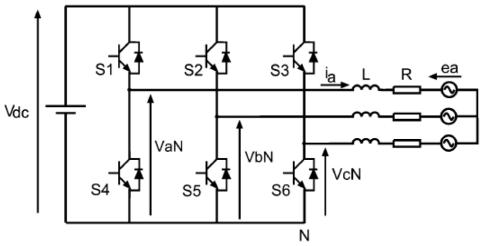

Figure 3: DSTATCOM power circuit

The switching state of the inverter is determined by the gating signal S_a, S_b, and S_c as follows [8]:

S_a = 1, if S_1 on and S_4 off
0, if S_1 off and S_4 on
S_b = 1, if S_1 on and S_4 off
0, if S_1 off and S_4 on
S_c= 1, if S_1 on and S_4 off
0, if S_1 off and S_4 on

And can be expressed in vectorial form as,

$$S=\frac{2}{3}(S_a + aS_b + a^2 S_c) \quad (2)$$

Where a=$e^{j2\pi/3}$

The output voltage space vector generated by the inverters are defined by,

$$V=\frac{2}{3}(V_{aN} + aV_{bN} + a^2 V_{cN}) \quad (3)$$

Where V_{aN}, V_{bN},V_{cN} is the phase to neutral voltages of the inverter. The load voltage vector v can be related to switching state vector I by

$$V=V_{dc}S \quad (4)$$

Where V_{dc} is the dc-link voltage.

Using MPC algorithm, appropriate voltage vector is selected so that the current THD can be reduced. Shape of current waveform can be maintained thus power factor correction can be obtained.

2.4 Discrete Time Load Model

In a unbalanced three-phase load, the current can be defined a space vector by[8],

$$i = \frac{2}{3}(i_a + ai_b + a^2 i_c) \quad (5)$$

Load current dynamics can be described by vector equation

$$V = Ri + L\frac{di}{dt} + e \quad (6)$$

Where R, is the load resistance, L is the load inductance the voltage generated by the inverter, e is the back emf.

A discrete-time model of the load current (6)for a sampling time T_s can be used to predict the future value of load current with the voltage and measured current at the kth sampling instant. Approximating the derivative

$$\frac{di}{dt} \approx \frac{i(k) - i(k-1)}{T_s} \quad (7)$$

And replacing it in (6), the following expression is obtained or the future load current:

$$i(k)=\frac{1}{RT_{s+L}}[Li(k-1) + T_s V(k) - T_s e(k)] \quad (8)$$

Where the term RT_s could be neglected if the sampling period is small enough and the load is mainly inductive.
One step forward in (8), the future load current can be determined by [8],

$$i(k+1)=\frac{1}{RT_{s+L}}[Li(k) + T_s V(k+1) - T_s e(k+1)] \quad (9)$$

Equation (9) is the predicted value of load current, where i(k) is the current value of load current. The predicted value of load current is compared with the reference value of load current to generate the desired switching pulses for DSTACOM.

2.5 Switching Pulse Selection

In the proposed predictive algorithm, the voltage vector whose current prediction is closed to the expected current reference is applied to the load at next sampling. Predicted value of lad current and reference current are transformed to Alpha-Beta plane. The selected vector will be the one that minimizes the quality function[8]

$$g = |i_\alpha{}^*(k+1) - i_\alpha(k+1)| + |i^*{}_\beta(k+1) - i_\beta(k+1)| \qquad (10)$$

Reference current value $i^*(k+1)$ is measured through d-q transformation and its future value is predicted by second order extrapolation.

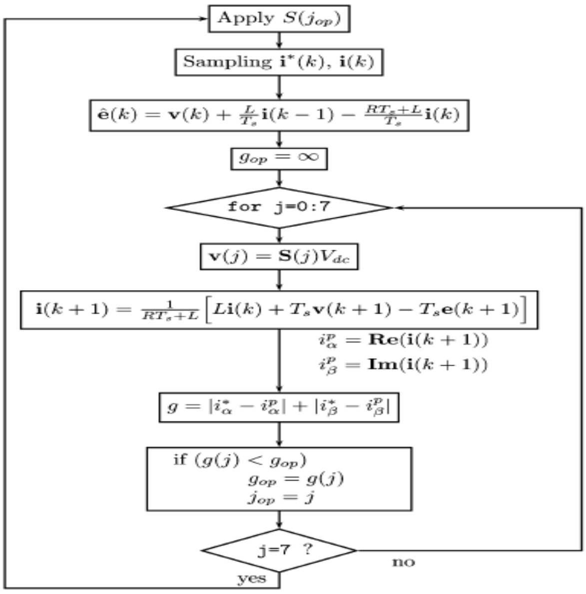

Figure 4: Implemented MPC_FC algorithm for power quality improvement

3. Deadbeat Control Algorithm

3.1 DSTATCOM Model

Deadbeat predictive algorithm uses the state space model of DSTATCOM for power quality improvement [12].Single phase equivalent circuit of DSTATCOM, is shown in Fig. 5,

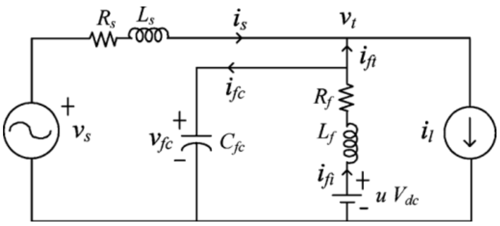

Figure 5: Single phase equivalent circuit of DSTATCOM.

The state space equation for the circuit taking current through inductor and voltage across capacitor as state variables,

$$\dot{x} = Ax + Bx \qquad (11)$$

Where,

$$A = \begin{bmatrix} 0 & \frac{1}{C_{fc}} & 0 \\ -\frac{1}{L_f} & -\frac{R_f}{L_f} & 0 \\ -\frac{1}{L_s} & 0 & -\frac{R_s}{L_s} \end{bmatrix},$$

$$B = \begin{bmatrix} 0 & -\frac{1}{C_{fc}} & 0 \\ \frac{V_{dc}}{L_f} & 0 & 0 \\ 0 & 0 & \frac{1}{L_s} \end{bmatrix}, \; x = [v_{fc} \quad i_{fi} \quad i_s]^t,$$

$$z = [u \quad i_{ft} \quad v_s]^t$$

Discrete form of the state space equation (11) is given as,

$$x(k+1) = Gx(k) + Hz(k) \qquad (12)$$

Where, G and H are matrices with a sampling time of T_d. For small T_d, the matrices G and H are calculated as follows:

$$G = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} = e^{AT_d} \approx I + AT_d + \frac{A^2 T_d{}^2}{2}$$

$$H = \begin{bmatrix} H_{11} & H_{12} & H_{13} \\ H_{21} & H_{22} & H_{23} \\ H_{31} & H_{32} & H_{33} \end{bmatrix} = \int_0^{T_d} e^{A\lambda} B d\lambda = \int_0^{T_d} (I + A\lambda)\, B d\lambda$$

Here, G_{13}, G_{23}, H_{13}, and H_{23} are found to be zero.
Discrete state space model of DSTATCOM is generated to calculate current reference.

3.2 Generation of deadbeat current control:

Reference current is calculated based on the fact that the predicted value of filter current should be same as reference value of filter current. Predicted value of filter current from (12), is given as following:

$$i_{fi}(k+1) = G_{11}v_{fc}(k) + G_{12}i_{fi}(k) + H_{11}u_c(k) + H_{12}i_{ft}(k) \qquad (13)$$

Cost function (J) is defined to minimize the error between predicted value of filter current and reference value of current.

$$J = \left[i_{fi}(k+1) - i_{fi}{}^*(k+1)\right]^2 \quad (14)$$

Where, $i_{fi}{}^*(k+1)$ is the predicted value of reference current Minimum of J is obtained by taking its derivative. The minimum value of cost function is obtained when,

$$i_{fi}(k+1) = i_{fi}{}^*(k+1) \qquad (15)$$

Reference current is obtained after replacing (15) in (13). Predicted value of reference current is calculated using, second order Lagrange's extrapolation

$$i_{fi}{}^*(k+1) = 3i_{fi}{}^*(k) - 3i_{fi}{}^*(k-1) + i_{fi}{}^*(k-2) \qquad (16)$$

Reference value of filter current is valid for a wide frequency range. Substituting (16) in (13) will yield to one step-ahead deadbeat current control law. The reference current control law from (13), (15), and (16) is given as,

$$u_c^*(k) = \frac{i_{fi}^*(k+1) - G_{11}v_{fc}(k) - G_{12}i_{fi}(k) - H_{12}i_{ft}(k)}{H_{11}} \quad (17)$$

3.3 Generation of deadbeat voltage control

From (12), the predicted value of capacitor voltage is,

$$v_{fc}(k+1) = G_{11}v_{fc}(k) + G_{12}i_{fi}(k) + H_{11}u(k) + H_{12}i_{ft}(k) \quad (18)$$

The procedure of obtaining reference current law is followed to obtain the reference voltage control law. It is given as follows [12]:

$$u_v^*(k) = \frac{v_t^*(k+1) - G_{11}v_{fc}(k) - G_{12}i_{fi}(k) - H_{12}i_{ft}(k)}{H_{11}} \quad (19)$$

Where ,
$v_{fc}(k+1) = v_t^*(k+1)$,$v_t^*(k+1) = 3v_t^*(k) - 3v_t^*(k-1) + v_t^*(k-2)$

3.4 Control of dc Link Voltage

Due to inverter losses and switching transient's capacitor voltage deviates from its reference value. The capacitor voltage control in CCM and VCM is achieved as following.
Control of dc Link Voltage in CCM: Average real power balance at the PCC will be

$$P_{pcc} = P_{lavg} + P_{loss} \quad (20)$$

Where, P_{pcc}, P_{lavg} and P_{loss} are the average PCC power, load power, and losses in the VSI, respectively. Power at PCC is determined by load angle. As load angle varies PCC power varies Hence, δ must be maintained constant to keep constant.

DC bus voltage of DSTATCOM is kept constant by supplying the inverter losses. As the capacitor voltage is maintained to its reference value, P_{loss} will be minimum and load angle is fixed. To compute load angle δ the DC-link voltage is compared with the reference voltage and error is passed through a PI controller.The output of the PI controller, which is load angle δ, is given as follows [11]:

$$\delta = K_{p\delta}e_{vdc} + K_{i\delta}\int e_{vdc}\,dt \quad (21)$$

Where $e_{vdc} = 2V_{dcreef} - (V_{dc1} + V_{dc2})$is the voltage error. Terms $K_{p\delta}$ and $K_{i\delta}$ are proportional and integral gains, respectively must lie between 0 to 90^0 for the power flow from the source to PCC.

3.5 Generation of current and voltage reference

PCC voltage and current waveform get distorted due to. Switching of inverters and unbalanced load.PCC voltage is extracted using fundamental positive sequence of filter current. The expressions for reference filter currents (i_{ftj}^*) are generated using instantaneous symmetrical components theories and are given as following:

Where, $\Delta_1^+ = \sum_{j=a,b,c}(V_{tj1}^+)^2$

The filter current is calculated from load current and inverter current. In equation (8), i_{lj} is load current and i_{sj}^* is the inverter current.

Average load power, P_{lavg}, is calculated using a moving average filter as follows:

$$P_{lavg} = \frac{1}{T}\int_{t_1}^{t_1+T}(V_{ta}i_{la} + V_{tb}i_{lb} + V_{tc}i_{lc}) \quad (23)$$

The PCC voltages (v_{tj1}^+) are reference voltages of shunt capacitors. Reference currents through these capacitors will lead their respective terminal voltages by 90^0. Therefore, reference currents through these capacitors will be finally, reference currents of the VSI will be given as

$$i_{fcj}^* = j\omega C_{fc}V_{tj1}^+ \quad (24)$$

Finally, reference currents of the VSI will be given as,

$$i_{fij}^* = i_{ftj}^* + i_{fcj}^* \quad (25)$$

Voltage disturbances in the system are compensated using DSTATCOM by injecting reactive current. Load voltages are maintained between 0.9 p.u. and 1.1 p.u., so as to maintain the injecting current minimum. Choosing suitable reference load voltage magnitude (V_t), and computing load angle from (21), the three-phase reference load voltages are[12],

$$\begin{aligned} v_{ta}^*(t) &= \sqrt{2}V_t^*\sin\omega t - \delta \\ v_{tb}^* &= \sqrt{2}V_t^*\sin\left(\omega t - \frac{2\pi}{3} - \delta\right) \quad (26) \\ v_{tc}^*(t) &= \sqrt{2}V_t^*\sin\left(\omega t + \frac{2\pi}{3} - \delta\right) \\ V_t^* &= \sqrt{V^2 - \left|\bar{I}_{la1}^+\right|X_s} - \left|\bar{I}_{la1}^+\right|R_s \end{aligned}$$

Where ω, is the system frequency.

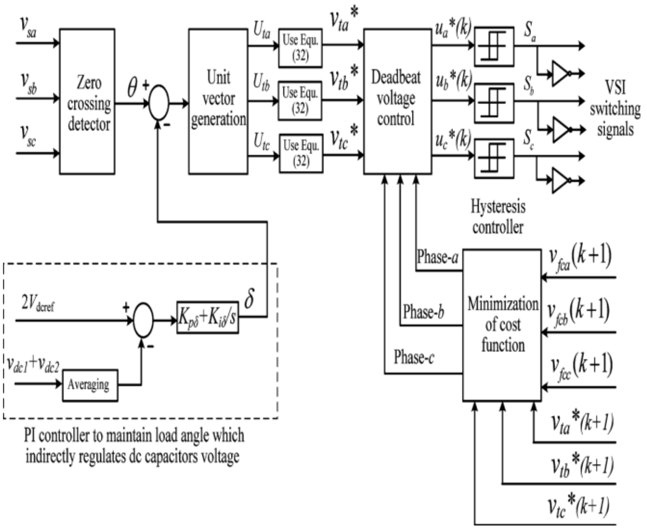

Figure 6: Overall block diagram for deadbeat controller

4. Simulation Result

MATLAB software is used to evaluate the effectiveness of deadbeat and predictive controller. Simulation parameters are given Table1.

4.1 Before Compensation

Terminal voltage and load current before compensation are plotted and is shown in fig 8 and 9. Due to the presence of nonlinear load the terminal voltages and current unbalanced and distorted.THD value of load current is19.11% and load voltage is 12.53%.

Table1: Simulation Parameters

System Quantities	Values
Source Voltage	415 V rms line to line,50 Hz.
Feeder impedance	Z_s=1+j3.14Ω
Linear load	Z_{la}=30+j62.8Ω Z_{lb}=40+j78.8Ω Z_{lc}=50+j50.24Ω
Non linear load	50+j62.8 Ω
VSI parameters	V_{dc}=650V,C_{dc}=2600μF, R_f=1 Ω,L_f=22mH,C_{fc}=5 μF

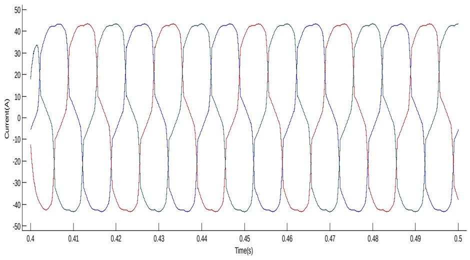

Figure 7: Simulation output of load current of three phase four wire system with non linear load and without DSTATCOM

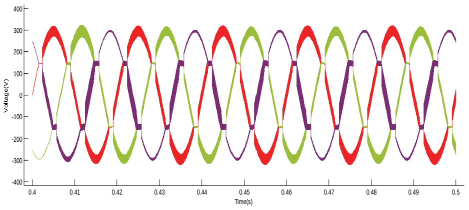

Figure 8: Simulation output of load voltage of three phase four wire system with non linear load and without DSTATCOM

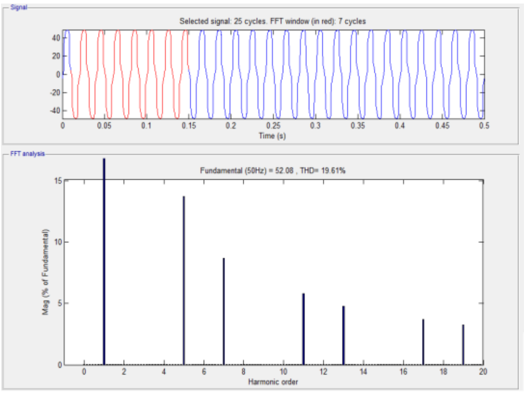

Figure 9: FFT analysis of PCC current of three phase three-wire system with non linear load and without DSTATCOM (THD=19.11%)

4.2 Nominal operation

Initially, the predictive controller method is considered. Fig 13 and 14 shows the terminal voltage and load, source current in phase a, b, and c, respectively. These waveforms are balanced and sinusoidal. The source current leads the terminal voltage which show that the compensator supplies reactive current to the source to overcome feeder drop, in addition to supplying load reactive and harmonic currents. Using the deadbeat Predictive controller method, terminal voltages and source currents in phases a, b, and c are shown in Fig 13 and fig 14.Thd value of load current is about 7.36% and that of load voltage is 3.53%

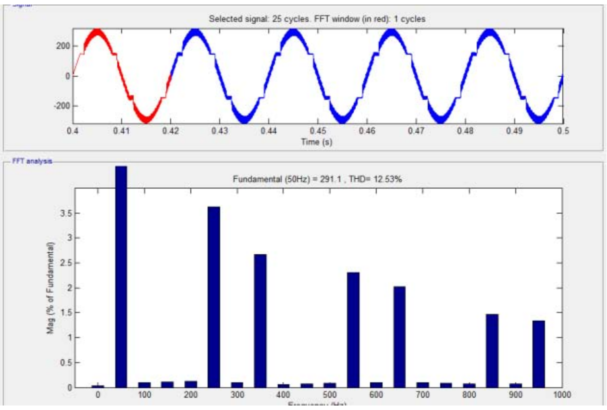

Figure 10: FFT analysis of PCC voltage of three phase three-wire system with non linear load and without DSTATCOM (THD=12.53%)

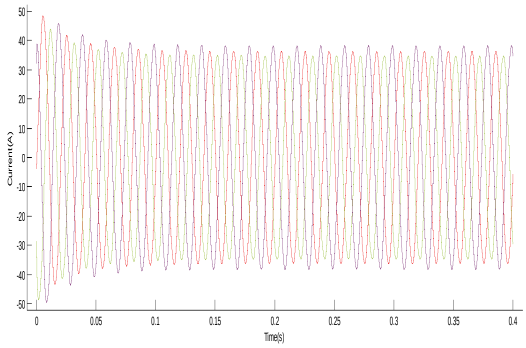

Figure 11: Simulation output of load current of three phase four wire system with non linear load and with Deadbeat controller

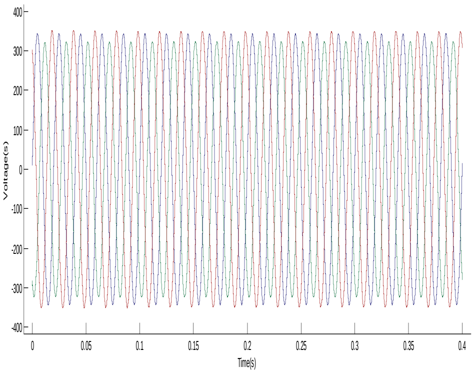

Figure 12: Simulation output of load voltage of three phase four wire system with non linear load and with Deadbeat controller

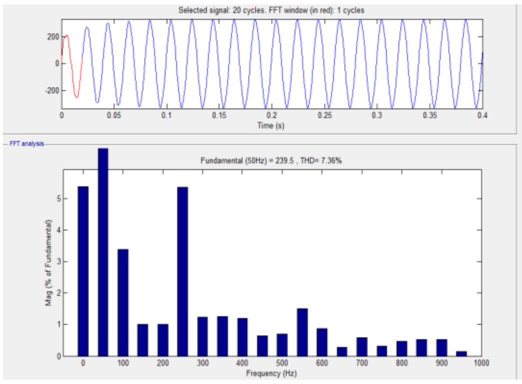

Figure 13: FFT analysis of load current of three phase three-wire system with non linear load and with deadbeat controller DSTATCOM (THD=7.36%)

Using the Model Predictive controller method, terminal voltages and load currents in phases a, b, and c are shown in Fig .16 and 17 Thd value of load current is about 1.13% and that of load voltage is 2.43%

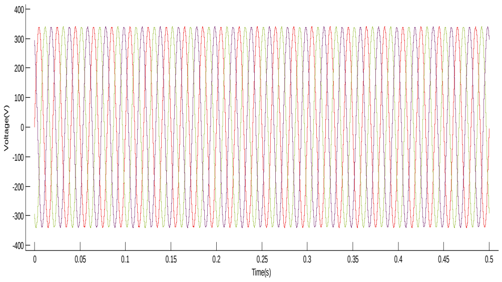

Figure 14: Simulation output of load voltage of three phase four wire system with non linear load and with Model Predictive controller

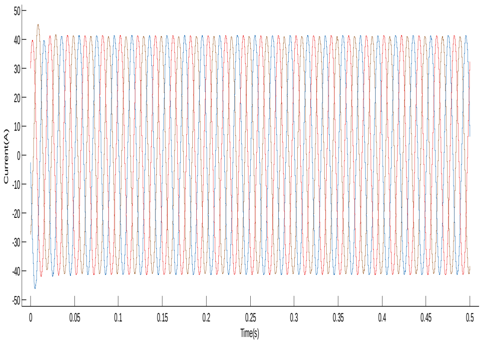

Figure 15: Simulation output of load current of three phase four wire system with non linear load and with Model Predictive controller

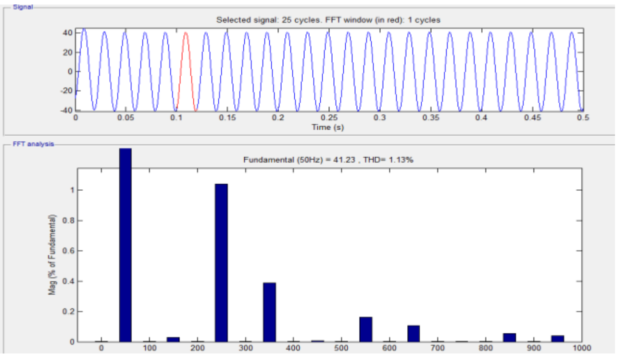

Figure 16: FFT analysis of PCC current of three phase four-wire system with non linear load and with MPC controller based DSTATCOM (THD=1.13%)

4.3 Power Factor Correction

Without DSTATCOM, the power factor of the system was about 0.8875. By connecting DSTATCOM to the distribution system, there is an improvement in power factor. Based on the controller used power factor improvement varies. While using a deadbeat controller the power factor of the system is 0.965Using MPC controller the power factor is 0.999.Using MPC controller terminal voltage and current are in phase and unity power factor can be obtained. Using SRF control strategy power factor of the system is 0.9232 Figure 19, 20,21 shows the voltage and current waveform before compensation and after compensation

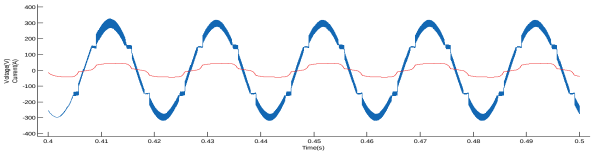

Figure 17: Voltage and current waveform without DSTATCOM

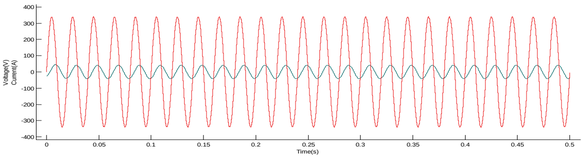

Figure 18: Voltage and current waveform with deadbeat control based Dstatcom

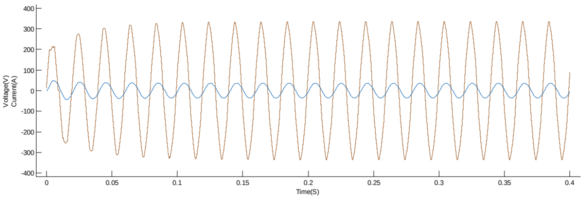

Figure 19: Voltage and current waveform with MPC control based Dstatcom

5. Conclusion

DSTACOM is a shunt compensating device used for power quality improvement. In this paper, comparative analysis between two predictive controllers applied to DSTATCOM for power quality improvement is done. In deadbeat predictive controller a reference load current is generated and switching pulses for DSTATCOM are generated based on this reference value. In model predictive controller model of the system can be used to predict the behavior of the load current for each switching state. Deadbeat and model predictive controllers will generate switching pulses to operate VSI, which in turn reduce distortion in current and voltage waveform. These controllers allow DSTATCOM to tackle power quality issues by providing power factor correction, harmonic elimination. MATLAB based simulink model is used to determine the effectiveness of the proposed controllers.

From the simulation result it is concluded that MPC controller based DSTATCOM has better performance than deadbeat predictive controller and linear controller based DSTATCOM. Using MPC controller the current THD can be reduced to 1.13% and unity power factor can be achieved. Thus Power quality improvement is achieved.

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