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Model Predictive Control of Shunt Active Filter for Power Quality Improvement in Distribution systems

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Abstract—The presence of nonlinear loads in the distribution system results in poor power quality parameters such as low total harmonic distortion (THD), poor distortion power factor and produces nearby communication interference. Shunt active power filters (SAF) are used for improving the power quality in high power distribution systems. The Shunt active filter controller has the low frequency voltage control loop for regulating the DC voltage of SAF capacitor and the faster acting current control loop for realizing the compensation current. Conventionally, the current and voltage controllers are realized by distinct hysteresis and PI controllers respectively. This paper discusses the finite control set Model Predictive Control (FCS- MPC) that realizes the voltage and current control of SAF. The reference current of SAF is calculated from the instantaneous PQ theory. The phase locked loop (PLL) is adopted for generating the reference value of compensation currents. A discrete time mathematical model of the SAF is presented and the design steps of FCS- MPC are explained. The control objectives such as compensation current error minimization and DC link voltage regulation are defined in cost functions. During each sampling interval, the controlled variables such as SAF current and DC voltage of the capacitor are predicted by the mathematical model. The predicted variables are assessed by the cost function minimization and the switching state that provides minimum cost function is selected and applied to the SAF. The performance of the FCS-MPC strategy for the current control of SAF is validated for sinusoidal and non-sinusoidal distribution system voltages in MATLAB-SIMULINK simulations.

Keywords— Active filter, Controller, Model predictive, Power quality, THD

I. INTRODUCTION

In recent years, there has been increased use of power electronic-based systems in industry and residential consumers for controlling the AC and DC powers, so as to increase the controllability and energy efficiency. The major power electronic controller applications in the residential consumer are UPS, SMPS, CFL Lamp and Inverter fed Air conditioning units. These power electronic controllers provide precise control of the power; serve as energy conditioners and energy savers among the residential consumers. Despite the numerous advantages, these power electronic-based systems possess the nonlinear characteristics and hence draw the harmonics and reactive components of current from the distribution grid. The harmonics of this nonlinear load results in poor power quality (PQ) parameters such as increase in total harmonic distortion (THD), poor distortion power factor, increased rms value of the current, high crest factor and excessive neutral current in three phase four wire distribution system. The presence of harmonics in the distribution utility results in increased losses and producing pulsating torque in the rotating machines; reduce the life time of other consumer equipment and produce electromagnetic interference with the nearby equipment. Further, these nonlinear loads are also responsible for the distortion of the voltage and current wave shapes of other nonpolluting loads connected to the same point of common coupling (PCC). Many electrical regulatory commissions and standards such as IEEE 519-1992, IEC 61000-3-2, etc. [1-3] recommend voltage and current distortion limits for consumers and utilities at various power levels. As the consumer equipment are connected to the distribution utility, in order to comply with the standards, proper power quality improvement method is necessary.

Conventionally, passive filters (L-C filters) have been used to improve the power quality. Though passive compensation is a simple approach, but they have several drawbacks such as inability to provide dynamic compensation, bulky size, cost, resonance problem, separate filters for each harmonics *etc* [4-6]. Power factor correction converters (PFC) are employed for AC to DC conversion in the utility as it provides the better PQ parameters at the source. The PFC converters contain the power electronic switches that are controlled suitably to draw the sinusoidal, in-phase current from the source. However, these PFC converters are limited to low power applications only, due to the high voltage and current stress in the switches. These shortcomings of passive compensation, PFC converters and increased concern of power quality has attracted wide attention of researchers in the design, analysis and implementation of various custom power devices with robust control and ease implementation, using high speed processing devices for three-phase, three-wire and three-phase, four-wire supply system [7]. The shunt active power filter (SAF) is one of the widely used compensation device to mitigate the power quality problems, by drawing or injecting the suitable compensating current from or to the utility, so that the voltage and current in the source can be maintained as sinusoidal. In addition, the SAF also compensates the reactive power requirement of the loads.

The current controlled voltage source converter and current source converter are reported for SAF topologies in the literatures. However, the voltage source converter gives higher efficiency, lower cost, lower size and simple structure as compared to current source converters. This paper employs a three-phase three wire SAF which is based on the current controlled voltage source converter.

The quality and performance of the SAF depends on the topology of SAF, methods of calculation of reference current by an appropriate control algorithm, supply voltage distortions, and the modulation techniques used to generate switching signals for PWM converter. A number of algorithms in time domain as well as frequency domain have been reported to calculate the reference current in the literature [8]. The frequency domain approach involves complex calculations and difficult to implement in the digital controllers. Hence, the instantaneous PQ theory which employs the time domain approach is implemented, for calculating the reference value of compensating current to SAF in this paper. This method is simple and involves only algebraic calculations and easier to implement in digital controllers [9].

The reference current which is calculated by the instantaneous PQ theory has been realized in SAF by a faster response current controller. The classical current control approach is classified in to two types namely hysteresis control and linear control using pulse width modulation (PWM). The hysteresis current control is conceptually simple and can be easily implemented in digital controllers. In PWM control, the reference current is compared with SAF current in PI controller and the control signal is compared with the triangular wave to generate PWM pulses. Further, for realizing the current control over the entire full cycle period, the DC voltage across the capacitor must be held at the value greater than the maximum value of the input voltage. The DC voltage is affected by the switching losses of SAF inverter switches. In addition, if the distribution grid voltage is unbalanced, the negative sequence power of the load will also result in low frequency oscillation of DC voltage across the capacitor. The DC voltage regulator section stabilizes the voltage across the capacitor despite these low frequency variations. The DC voltage stabilization is accomplished generally by using a PI controller for voltage control loop. Since the current control loop is always faster than voltage control loop, the reference current tracking is usually carried out by current control.

With the advent of modern digital controllers like DSP and FPGA, the more complex control strategy can be easily implemented in digital control platforms. In present days, all control methods can be implemented in digital control platforms running at discrete time steps. Hence, Model Predictive Control (MPC) has been recently implemented for power electronic converters current control. MPC has several advantages like having faster tracking response, suitability to handle multivariable system, feasibility of handling system non linearity and simple treatment of system constraints [9-15]. MPC involves more calculations and it can be implemented very well with the recently developed fastest controllers like DSP and FPGA.

SAF is a multi- controlled variable, nonlinear system of hybrid nature including linear and nonlinear parts and finite number of switching devices. Hence, MPC has been applied to the compensation current control and voltage regulation of DC capacitor of SAF. In MPC, the future performance of the controlled variables is predicted by the discrete model of the system. MPC uses this information to determine the best control action by a cost function minimization procedure. MPC does not require a modulator for realizing current control and operates with fixed switching frequency [10].

MPC can be classified in to controller employing continuous control set and finite control set for control actions. Finite Control Set model predictive control (FCS-MPC) is the predictive control strategy applied to power electronic converters which has finite number of possible switching actions. SAF has 6 switches and 8 distinct valid switching states. At each sampling time, the cost function is estimated for all the possible switching states and the switching function that minimize the cost function is selected and applied to SAF. FCS-MPC has been effectively implemented for the current control of three phase inverters [11-12], power control of active front end rectifiers, SAF [13-15] and matrix converters [16].

This paper presents the method of application of Finite Control Set Model Predictive Control (FCS-MPC) strategy to the shunt active power filter for power quality improvement in the distribution system. The instantaneous PQ theory is adopted for the calculation of the reference current. The system description and mathematical modelling of SAF is explained in section II and Section III. The section 1V explains the design steps involved for FCS-MPC of SAF. The performance of FCS-MPC of SAF is validated for sinusoidal and non-sinusoidal distribution system voltages in MATLAB SIMULINK. The simulation results are presented in section V. Finally, the conclusions are drawn on section VI.

II. SYSTEM DESCRIPTION

The Shunt Active Filter (SAF) is connected to the point of common coupling (PCC) to improve the power quality parameters of the distribution system as shown in Figure. 1. The SAF is realized by a voltage source inverter (VSI) with six IGBT switches and connected to the PCC through interface reactor. The DC input of SAF is connected with a capacitor. The capacitor supplies the reactive power and harmonic power required by the nonlinear loads. The SAF has the capability of injecting the necessary reactive, harmonic current of nonlinear loads connected in the distribution system. This results in the transfer of real power alone from the distribution system to the load. In addition, the SAF also draws the real power from the distribution system to compensate the switching losses incurred in the inverter switches and to maintain the DC voltage of SAF capacitor with in smaller variation limits.

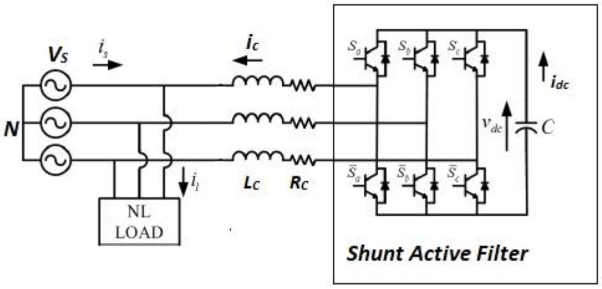

Figure. 1. Schematic diagram of Shunt active filter

The switching states of the VSI switches of SAF are described as switching functions $S_a(k)$, $S_b(k)$, $S_c(k)$. The switching function has the value of 1 if the top switch of the leg is ON; bottom switch of the leg is OFF and vice versa for the switching function value 0. Since there are three number of phase legs with 2 different switching states, 8 different switching states are possible. Out of them, it contains 2 null states ((0,0,0) and (1,1,1)) and 6 active states. The space vector of the inverter switching states and the inverter voltages are defined by

$$S = \frac{2}{3}(S_a + a\,S_b + a^2 S_c) \tag{1}$$

$$v = \frac{2}{3}(v_{aN} + a\,v_{bN} + a^2 v_{cN}) \tag{2}$$

where $a = e^{j2\pi/3}$, v_{aN}, v_{bN}, v_{cN} are the phase to neutral voltages of legs a, b and c.

The output voltage of the inverter is expressed in terms of switching functions by

$$v_o = S.V_c \tag{3}$$

where V_c is the DC voltage across the Capacitor.

III. MATHEMATICAL MODEL OF SHUNT ACTIVE FILTER

Let

R_c	Resistance of SAF in Ohm
L_c	Inductance of SAF in Henry
$V_{ao}(t)$, V_{bo} (t), $V_{co}(t)$	Voltage of each phase leg with respect to negative point of DC voltage 'O'
$V_{sa}(t)$, $V_{sb}(t)$, $V_{sc}(t)$	Phase value of source voltage
$V_o(t)$	Voltage between neutral point of the source 'N' and negative point of DC voltage 'O'
$V_c(t)$	DC Voltage across the SAF capacitor
$I_{ca}(t)$, $I_{cb}(t)$, $I_{cc}(t)$	Compensation current injected by the SAF

By applying Kirchhoff's Voltage law, the inverter voltage can be expressed in terms of filter currents as following.

$$\begin{aligned} V_{ao}(t) &= R_C.I_{ca}(t) + L_c\,.\frac{dI_{ca}(t)}{dt} + V_{sa}(t) + V_o(t) \\ V_{bo}(t) &= R_c.I_{cb}(t) + L_c\,.\frac{dI_{cb}(t)}{dt} + V_{sb}(t) + V_0(t) \\ V_{co}(t) &= R_c.I_{cc}(t) + L_c\,.\frac{dI_{cc}(t)}{dt} + V_{sc}(t) + V_0(t) \end{aligned} \tag{4}$$

Let $S_a(t), S_b(t), S_c(t)$ are the switching functions of phase legs a, b and c respectively.

For a balanced system, the equation can be further simplified and it results in

$$V_o(t) = \frac{(2\,S_a(t)+2S_b(t)+2S_c(t)-3)}{6} V_c(t) \tag{5}$$

By substituting (5) in (4), the continuous time current of SAF is derived as

$$\begin{aligned} \frac{dI_{ca}(t)}{dt} &= -\frac{R_c}{L_c}.I_{ca}(t) + \frac{V_{dc}(t)}{3L_c}\big(\,2S_a(t) - S_b(t) - S_c(t)\big) + \frac{V_{sa}(t)}{L_c} \\ \frac{dI_{cb}(t)}{dt} &= -\frac{R_c}{L_c}.I_{cb}(t) + \frac{V_{dc}(t)}{3L_c}\big(\,2S_b(t) - S_c(t) - S_a(t)\big) + \frac{V_{sb}(t)}{L_c} \\ \frac{dI_{cc}(t)}{dt} &= -\frac{R_c}{L_c}.I_{cc}(t) + \frac{V_{dc}(t)}{3L_c}\big(\,2S_c(t) - S_a(t) - S_b(t)\big) + \frac{V_{sc}(t)}{L_c} \end{aligned} \tag{6}$$

The continuous time model equation of SAF is converted in to discrete time equation for implementing in digital controllers. The Forward Euler transformation is applied to equation (6) to obtain discrete time model.

$$\frac{di(t)}{dt} = \frac{i(k+1) - i(k)}{T_s} \qquad (7)$$

where $i(k+1)$ is the current at instant (k+1), $i(k)$ is the current at instant (k) and T_s is the sampling period.

The corresponding discrete time equations of SAF current are

$$I_{ca}(k+1) = \left(1 - \frac{R_c T_s}{L_c}\right) I_{ca}(k) + \frac{V_c(k)}{3L_c}\left(2S_a(k) - S_b(k) - S_c(k)\right) T_s + \frac{V_{sa}(k)}{L_c} T_s$$

$$I_{cb}(k+1) = \left(1 - \frac{R_c T_s}{L_c}\right) I_{cb}(k) + \frac{V_c(k)}{3L_c}\left(2S_b(k) - S_a(k) - S_c(k)\right) T_s + \frac{V_{sb}(k)}{L_c} T_s$$

$$I_{cc}(k+1) = \left(1 - \frac{R_c T_s}{L_c}\right) I_{cc}(k) + \frac{V_c(k)}{3L_c}\left(2S_c(k) - S_a(k) - S_b(k)\right) T_s + \frac{V_{sc}(k)}{L_c} T_s \qquad (8)$$

By applying KCL, the capacitor voltage is expressed in terms of switching states and SAF currents.

$$C.\frac{dV_c(t)}{dt} = S_a(t).I_{ca}(t) + S_b(t).I_{cb}(t) + S_c(t).(-I_{ca}(t) - I_{cb}(t))$$

$$\frac{dV_c(t)}{dt} = \frac{1}{C}\left(\left(I_{ca}(t).\left(S_a(t) - S_c(t)\right) + I_{cb}(t).\left(S_b(t) - S_c(t)\right) \right.\right. \qquad (9)$$

The corresponding discrete time equations are

$$V_c(k+1) = V_c(k) + \frac{T_s}{C}\left((S_a(k) - S_c(k))\, I_{ca}(k)\right) + \frac{T_s}{C}\left((S_b(k) - S_c(k))\, I_{cb}(k)\right) \qquad (10)$$

IV. FINITE CONTROL SET MODEL PREDICTIVE CONTROL OF SHUNT ACTIVE FILTER

Model Predictive Control is an advanced control technique that uses the receding horizon control strategy for determining the optimal control actions. The Predictive model of the system is represented in discrete time domain. This predictive model is used by the MPC controller to predict the future value of the controlled variables. The desired behavior of the system is represented in terms of cost functions. The controller predicts the future value of the controlled variables and the cost function is evaluated for all switching actions. MPC is an optimization problem that involves minimizing the cost function J for a predefined prediction horizon N. This will result in a sequence of N optimal control actions and the controller will select the first one of the sequence. The optimization problem is solved at each sampling instant using the new set of predicted data and subsequently new set of control action is derived and applied at each sampling interval.

The steps involved in the design of finite control set MPC for SAF is detailed below.

1. The discrete time mathematical model of the SAF (equation 8 and 10) is determined by identifying all the switching states and its relation to output current and input DC voltage. This plant model is used as a predictive model to predict the future behavior of the controlled variables until a predefined horizon time N. The switching function of inverter switches($S_x(k),\ x = a,b,c$) are the manipulated variables and the SAF current ($I_{cx}(k), x = a,b,c$) and DC link voltage($V_C(k)$) are the measured variables.

2. The cost function of the system which represents the desired behavior of the system is defined.

3. MPC control algorithm performs the optimal control action by minimizing the cost function.

A. Model Predictive Control design steps

The finite control set MPC is shown in Figure. 2. This controller uses the discrete time model equations (8) and (10) of SAF to predict the future value of the controlled variables (SAF current ($I_{cx}(k+1), x = a,b,c$), DC voltage across the capacitor ($V_C(k+1)$) from the manipulated variable ($S_x(k), x = a,b,c$) at kth instant for all possible switching actions. The inverter has 8 distinct switching states. The controller select the optimum switching state based on the optimization criterion. The steps involved design process of MPC controller is listed below.

1. Measurement of voltage

MPC requires measurement of Source voltage ($V_{sx}(k), x = a,b,c$) and DC voltage across Capacitor ($V_C(k)$) at kth instant.

2. Reference current calculation and extrapolation

Reference current of SAF in orthogonal coordinates ($I_{cx}(k)^*, x = \alpha,\beta$) is calculated using instantaneous PQ theory at kth instant. Since the determination of cost function is performed at (k+1)th sampling instant, the reference current that is calculated at kth instant is extrapolated to future state. For higher sampling frequency, the calculated reference current does not significantly change in one sampling interval, hence no extrapolation is required.

$$I_{cx}(k+1)^* = I_{cx}(k)^*, x = \alpha,\beta \qquad (11)$$

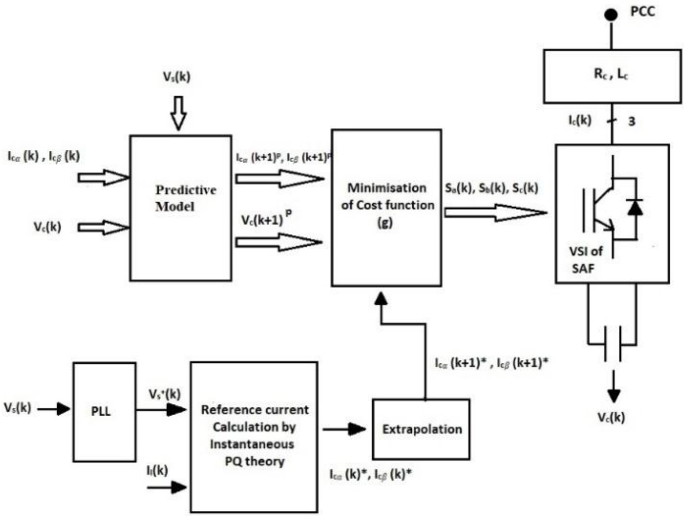

Figure.2. Finite control set Model predictive control of Shunt active filter

3. SAF current prediction

In finite control set MPC, the future value of SAF current $I_{cx}(k+1)^P$ and Capacitor voltage $V_C(k+1)^P$ are predicted from the measured value of capacitor DC voltage $(V_C(k))$ and source voltage $(V_{sx}(k), x = a, b, c)$ for all possible switching states of the inverter switches by using the discrete model equation (8,10).

4. Cost function minimization

The control scheme has two objectives. The first objective is to obtain the source current with lower THD value and nearly unity p.f. This can be accomplished only if the SAF injects the required compensating current as dictated by the reference current. Here, the positive sequence component of source voltage ($V_{sx}{}^+$) is used for calculating the reference currents (I_{cx}*) to nullify the effects of unbalance and harmonic content of source voltage. This will result in significant changes in DC voltage across the capacitor as it supplies the negative sequence power of load in addition to the switching losses of the inverter. But maintaining the constant DC voltage is mandatory to produce the required SAF current. Hence maintaining the DC link voltage with in smaller variation limits is the second objective of the control scheme. These two control objectives such as minimizing the current error between compensator current $I_{cx}(k+1)^P$ and reference current $I_{cx}(k+1)^*$ and regulating the DC voltage across capacitor $V_c(k+1)$ can be specified in the form of cost function.The cost function is expressed as below.

$$g_1 = |I_{cx}(k+1)^* - I_{cx}(k+1)^P| \ , x = \alpha, \beta$$
$$g_2 = |V_C(k+1)^* - V_C(k+1)^P|$$
$$g = \lambda_1 g_1 + \lambda_2 g_2 \tag{12}$$

where, g is the cost function, λ_1 and λ_2 are weighing functions.

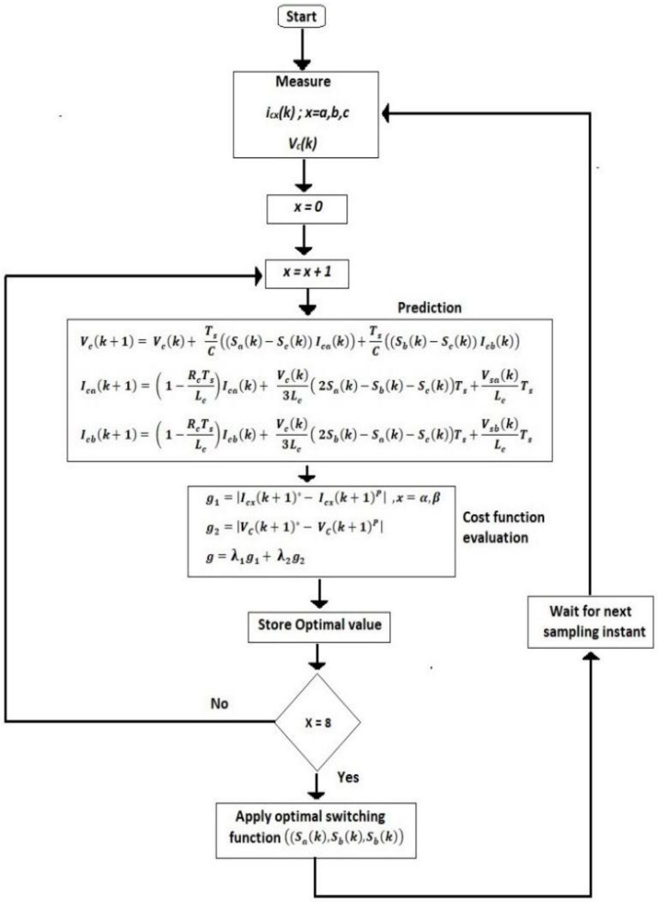

Figure. 3. Flow chart diagram for Finite control set Model predictive control of Shunt active filter

The cost function *'g'* is estimated for each switching states of the inverter switches. The main objective of the control algorithm is to obtain the cost function *'g'* value closest to zero. At each sampling interval, the SAF currents and DC voltage across capacitor are predicted for 8 different switching states and compared with the reference value to calculate cost function. The switching state that will result in minimum cost function value is selected and the corresponding switching signals are generated and applied to the inverter switches at the next sampling instant (k+1). The flow chat for FCS MPC control algorithm of SAF is shown in Figure. 3.

V. RESULTS AND DISCUSSION

The Finite Control Set Model Predictive Control (FCS-MPC) algorithm of shunt active filter for power quality improvement in the 3 phase 3 wire distribution system has been simulated in MATLAB SIMULINK.

The distribution system line voltage is set as 380 Volts (rms) and the 3 phase diode bridge rectifier fed RL load is connected as the nonlinear load in the distribution system. The shunt active filter is connected at PCC for improving the power quality at the distribution AC mains. The parameters of SAF are listed in Table.1. The reference current of SAF is calculated by instantaneous PQ theory. The FCS-MPC algorithm is implemented in MATLAB SIMULINK as embedded MATLAB function.

Table 1. System parameters

Parameters	Values
Source voltage	380 V rms (line value)
Capacitor	1100 μF, 700 V
Interfacing reactor	0.4 mH
Interfacing resistance	0.1 Ω
DC link voltage	600 V
Nonlinear load	3 phase Diode Bridge rectifier with RL load

The simulation tests have been performed in the sinusoidal and non-sinusoidal distribution system voltage conditions, to validate the performance of FCS MPC of SAF for the power quality improvement in the distribution AC mains.

Case 1. Sinusoidal balanced distribution system voltage with nonlinear load

Initially the sinusoidal distribution system voltage is applied to the nonlinear load. The load current (I_L) waveform is shown in Figure. 4.1. The reference value of DC voltage across the SAF capacitor is set as 600 V. Since the 6 pulse diode bridge rectifier is connected as the nonlinear load, the harmonic order of (6n $\pm$1) is evident in the load harmonic spectrum which is shown in Figure. 4.2. The THD of nonlinear load current is 27.37 %. The compensation current is calculated by the instantaneous PQ theory.

The finite control set model predictive control is implemented for determining the optimal switching of IGBT switches in VSI of SAF. The cost function is evaluated for all the switching states and the switching function that renders the minimal cost function value is selected and applied to the switches of VSI. The source current is improved to sinusoidal wave form with p.f closer to unity as shown in Figure 4.1. The THD of source current is improved to 3.68% and the harmonic spectrum of source current is shown in Figure 4.3. The various wave forms for sinusoidal distribution system voltage is shown in Figure 4.1.

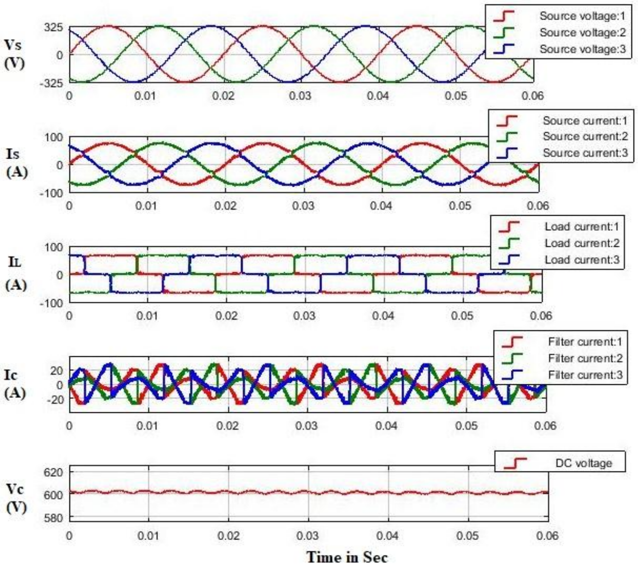

Figure. 4.1. Wave forms of sinusoidal distribution system voltage (V_S), Source current (I_S), Load current (I_L), filter current (I_C) and DC voltage of capacitor (V_C)

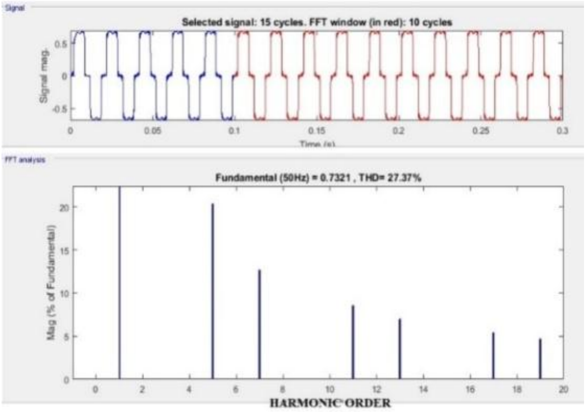

Figure. 4.2. Harmonic spectrum of load current for sinusoidal distribution system voltage

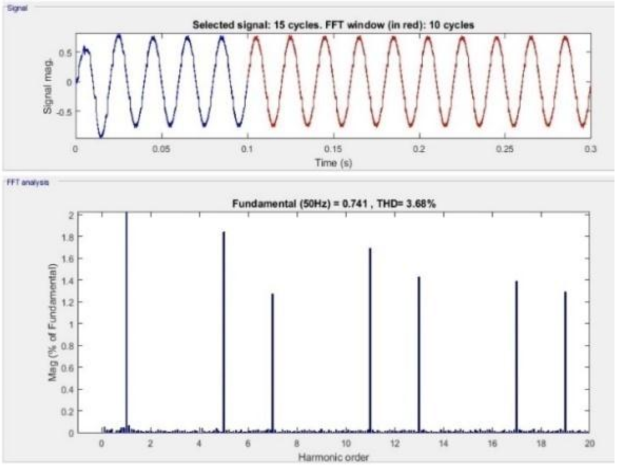

Fig. 4.3. Harmonic spectrum of source current for sinusoidal distribution system voltage

Case 2. Non-Sinusoidal balanced distribution system voltage with nonlinear load

In the next case, in order to realize the performance of the SAF controller in the non-sinusoidal distribution system voltage conditions, the fifth order harmonic and seventh order harmonic of 0.1 per unit is superimposed with the sinusoidal voltage and applied to the nonlinear load. The reference value of DC voltage across the SAF capacitor is set as 600 V. The THD of non-sinusoidal distribution system voltage is 14% and its harmonic spectrum is shown in Figure 5.2. The load current (I_L) waveform is shown in Figure 5.1. The THD of nonlinear load current is 29.78 % and its harmonic spectrum is shown in Figure 5.3. The compensation current is calculated by the instantaneous PQ theory. The PLL is adopted for extracting the positive sequence component of the voltage for determining the reference current of SAF. The finite control set model predictive control is implemented for determining the optimal switching of IGBT switches in VSI of SAF. The cost function is evaluated for all the switching states and the switching function that provides the minimal cost function value is selected and applied to the switches of VSI. The source current is improved to sinusoidal wave form with p.f closer to unity as shown in Figure 5.1. The THD of source current is improved to 4.18% despite the source voltage THD of 14%.

The harmonic spectrum of source current is shown in Figure.5.4. The various wave forms for non-sinusoidal distribution system voltage is shown in Figure5.1.

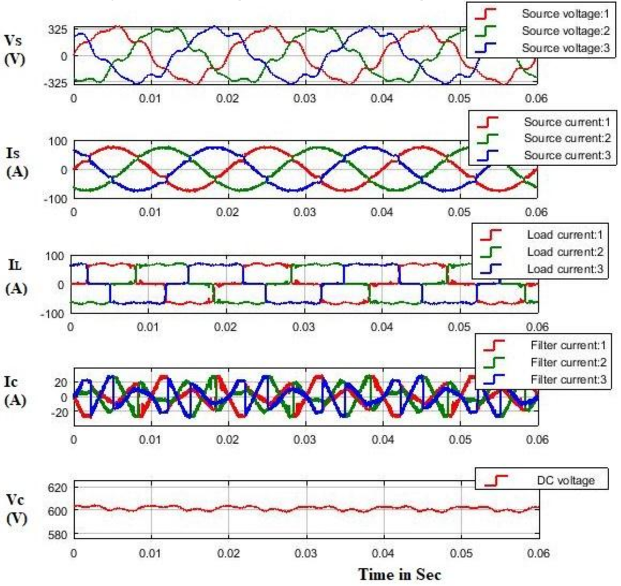

Figure. 5.1. Wave forms of non-sinusoidal distribution system voltage (V_S), Source current (I_S), Load current (I_L), filter current (I_C) and DC voltage of capacitor (V_C)

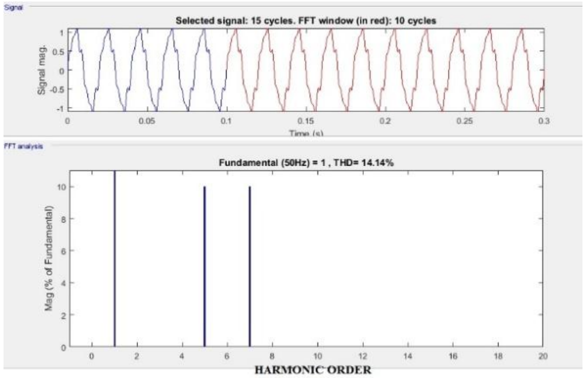

Figure. 5.2. Harmonic spectrum of non-sinusoidal distribution system voltage

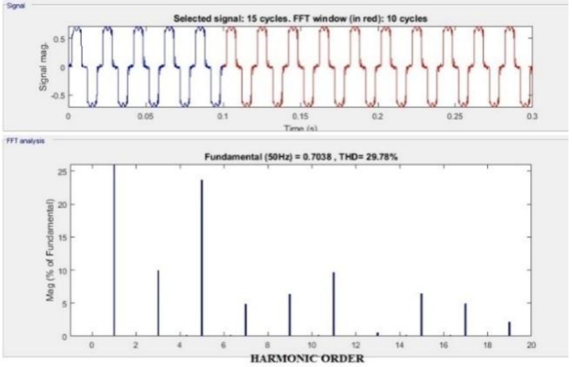

Figure. 5.3. Harmonic spectrum of load current for non-sinusoidal distribution system voltage

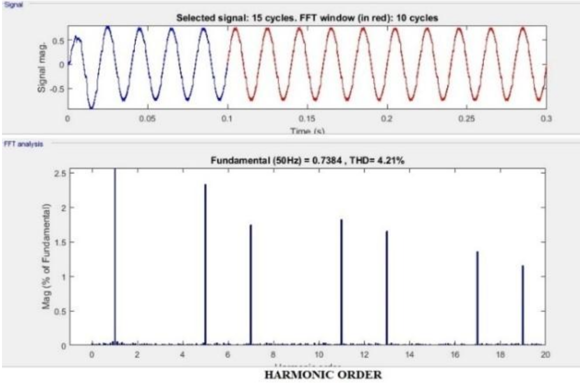

Figure. 5.4. Harmonic spectrum of source current for non-sinusoidal distribution system voltage

VI. CONCLUSION

Power quality improvement in the modern distribution system which employs power electronic loads is an emerging area of research in electrical engineering. The use of shunt active filter for improving the power quality in the distribution mains is vital for delivering the efficient and reliable power to the loads. The Finite control set model predictive control which is conceptually simple and easy to implement in modern digital controllers is adopted for the current control of SAF and DC voltage control of SAF capacitor. The control action is based on the system prediction model. The FCS MPC algorithm predicts the SAF current and DC voltage of capacitor, using the system prediction model for all the switching states and the cost function optimization is accomplished between each switching intervals. The simulation results validate the performance of FCS MPC of SAF in the sinusoidal and non-sinusoidal distribution system voltage conditions. From the simulation results, it is inferred that the power quality parameters are improved to the IEC standards.

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