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FCS-MPC DYNAMIC REACTIVE POWER CONTROL USING HYBRID ACTIVE POWER FILTER

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ABSTRACT
The paper discusses design of reactive power control using FCS-MPC controller implemented through Simulink (proposed), use of hybrid active filter to control and improve reactive power is also discussed in brief. The implementation showed that multivariable cost function presented for converters with LCL filters are also suitable to control hybrid active power filter. An adaptive notch filter is also considered during the implementation. The implementation of FCS-MPC design presented here can be considered as an alternative to classical reactive power control, which offers proper control performance with better dynamic response when compared with other techniques.

INTRODUCTION
The economy of nation is largely influenced by unit of electricity generated, transmitted and distributed .The continuous research developments undergoing are lead to find alternate solutions so as to meet the optimum efficiency during this power transmission and distribution of power is concern. As, the Electrical power system concerned ,Power system is said to be stable only if the unwanted disturbances parameters like harmonics present in reactive power, poor voltage regulation, low power factors, low transmission efficiency are taken care so as to avoid any unwanted variations which may result in inefficient operation of power system. As Today's the power system is very complex and interconnected; we need to improve power utilization to maintain security and reliability of the power system. As some transmission lines are overloaded and some of them are loaded below the limit by which voltage profile deteriorate and hence the system stability decreases hence it is most important to control the power flow in the transmission line. The major challenges for a power system to be a stable is a major serious importance to be considered due to variations resulting due to harmonics produced in generating voltage as well ,voltage distributed towards the consumers are considered. The various problems and its causes related to the dynamics of reactive current can cause problems in voltage regulation and stability deteriorating power quality and increasing system losses. Thus power quality is becoming more and more serious with each passing day. In order to minimize these harmonics, control strategies for extracting the Finite Control Set Model predictive control for dynamic reactive power compensation with hybrid active power filter (HAPF) need to be designed and compared evaluating their performance under different source conditions with FCS-MPC controllers in Matlab /Simulink model. The hybrid active power filter plays a very important role in almost all industrial applications, agricultural and domestic applications of electrical power is concerned which usually has the combinations of active and passive components in order to reduce the power rate power electronic devices, allowing high power applications with reduced costs during their design and manufacture.

In an alternating current power system, Power system comprises of two components, active power and reactive power. Useful work is accomplished by active power while the reactive power improves voltage stability and avoids voltage collapse resulting due harmonics present in sine wave of ac quantity. By regulation of reactive power the parameters of a power system like Utilization of active power, Voltage stability, Power factor, System efficiency, Energy cost and Power quality can be controlled. The following are various reasons why reactive power control is essential:

1. Voltage Control:
2. Electrical Blackouts
3. Proper working of various devices/machines

The quality of electrical power in a network is a major concern which has to be examined with caution in order to achieve a reliable electrical power system network. Reactive power compensation is a means for realizing the goal of a qualitative and reliable electrical power system. The reactive power compensation technologies are widely used and some of them include such as Synchronous Condenser, Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM),Hybrid active power filters (HAPF),Finite Control Set Model Predictive Control (FCS-MPC).

a.) Synchronous Condenser
b.) Static VAR Compensator
c.) Static Synchronous Compensator

LITERATURE REVIEW

S. Khalid & Bharti Dwivedi discussed innovative technology management by critical analysis about power quality problems, issues, related international standards, and their effect in life and the corrective measures using different means. Shazma Khan, Balvinder Singh, Prachi Makhija (2017) explained about power quality and discussed about appropriate standards for various power quality issues and also provided solution to major power quality problems with use of custom power devices like - STS, SCL, SCB, DVR, STATCOM and UPFC etc. Aishvarya Narain and S. K. Srivastava (2015) described the study of various reactive power compensation techniques needed for any power system using FACTS devices such as SSSC, TCR, TCSC, STATCOM and UPFC.At the end comparison of various FACTS devices are done. Also the need of reactive power compensation and the various FACTS devices used for compensation. From the comparison study revealed that UPFC is better for voltage control and lad flow but for low level application STATCOM is also shows better results. From this they concluded that FACT controller will play a very vital role for reactive power compensation in electrical power system. Marwa Ben Said-Romdhane, Manel Jebali Ben Ghorbal and Sondes Skander-Mustapha (2018) investigated on the VOC and the ISMPC for both Converters of the load emulator and shown that the ISMPC presents good current quality (low current THD) as well as a good robustness compared to VOC, which is more sensitive to parameters variations. Jose Rodriguez, Marian P. Kazmierkowski, and Jos´e R. Espinoza addressed to some of the latest contributions on the application of Finite Control Set Model Predictive Control (FCS-MPC) in Power Electronics. They showed that how the use of FCS-MPC provides a simple and efficient computational realization for different control objectives in Power Electronics. Some applications of this technology in drives, active filters, power conditioning, distributed generation and renewable energy are covered. Niklas Panten, Nils Hoffmann and Friedrich W. Fuchs In this work, it is shown that FCS-MPC is able to handle complex control systems like grid connected converters with LCL filters. In this case, resonance issues are addressed by active damping approaches like virtual-resistance damping or multi-variable control. Besides converter-side current feedback, this work presents and compares three new feedback approaches including multi-variable control and direct line current control based on FCS-MPC. Silvia Costa Ferreira, Robson B. Gonzatti, Rondineli R. Pereira (2017) applied finite control set model predictive control (FCS-MPC) for dynamic reactive power compensation using a hybrid active power filter (HAPF). The results have shown that the multivariable cost function for converters with LCL-Filters, are suitable to control the HAPF. It was demonstrated the inverter current control is not enough to guarantee proper operation of the FCS-MPC algorithm. An adaptive notch filter is used to implement the active damping and harmonic blocking algorithm. It assures adequate THD of hybrid filter current in steady-state. The performance of the FCS-MPC has been experimentally evaluated in a HAPF prototype. As a result, the presented control strategy based on FCS-MPC and adaptive filters can be considered as an alternative to classical reactive power control. It offers proper control performance with better dynamic response when compared to others in the literature. Govindaraj.V, Priya.M (2018) reviewed hybrid active power filters topologies and different controllers for enhancement of power quality and provided detailed study of HAPF technology to researchers and field engineers dealing with power quality.

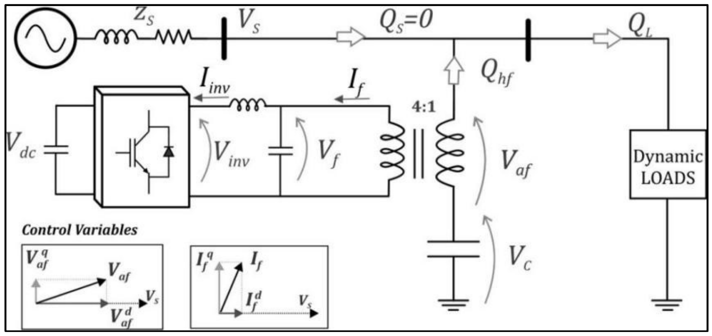
A detailed literature survey of HAPF is presented to provide a clear perception on various aspects of HAPF to the researchers and engineers working in this field. The review and classification of published work in this field shows that there has been a significant increase in research of hybrid active power filters and related control method. A large number of HAPF configurations are available to compensate harmonics. Even though control strategies of Hybrid Active Power Filters have advanced greatly, still more study needs to be done to maintain near perfect power quality as more and more sensitive as well as complex loads are coming into the power networks. Rahul Kumar Patel, S. Subha (2014) presented adaptive dc-link voltage controlled LC coupling hybrid active filters for reduced switching losses and switching noise under the reactive power compensation. The adaptive DC link voltage controller for three phase four wire system LC-Hybrid Active power factor filters (LC- HAPF) is proposed. In this proposed system the reactive power compensation range as well as dc link voltage can be adaptively changed according to different inductive loading situations. The simulation results of three phase four wire LC-Hybrid Active power filters are presented to verify the validate and the effectiveness of the adaptive dc-link voltage-controlled LC-HAPF for reactive power compensation. An adaptive dc-link voltage-controlled LC-HAPF with dynamic reactive power compensation capability in the three phase four-wire system is proposed in this paper. In order to implement the adaptive dc-link voltage control algorithm, the LC-HAPF required minimum dc-link voltage for compensating different reactive power is deduced and its adaptive control block diagram is also built. Venkata Krishna Gonuguntala, Anke Fröbel and Ralf Vick (2018) Analysis and comparison of the performance of direct MPC is done with hysteresis current control for SAPF application. The impact of extrapolation methods on the compensation capabilities of SAPF is also presented. One of the drawbacks of direct MPC technique is its spread switching frequency behavior. To avoid this, a modulation method is applied in the control algorithm to operate the SAPF at fixed switching frequency. Also the direct MPC based active filter controller is presented for shunt active power filtering application. The simulation results verify the compensation capabilities of shunt active power filter, the THD of grid current has been reduced from 25.02 % to 3.69 %. The performance variation due to parameter error is in the future scope.

METHODOLOGY

Methodology adopted for this research work is as below

1) Collection and study of relevant literature to arrive at central idea of the proposed work.
2) Study of power quality standards, issues, mitigation techniques and its consequences of hybrid active power filter.
3) Analysis and Simulation design of hybrid Active Power Filter(HAPF) with MPC
4) To carryout analysis of Hybrid Active Power Filter (HAPF) with active and reactive power (P-Q) and instantaneous active and reactive Power
5) Simulation of entire scheme in simulation software to study the various performance Parameters such as Total Harmonic Distortion, exchange of active and reactive power etc.
6) Step To Implement MPC Algorithm
   1. Measure state variables: V, f, I inv, I f, Vs , I L and V dc
   2. Apply the optimum switching state S opt.
   3. Obtain the p.u. values of the system variables.
   4. Estimate by applying the ANF to the load current.
   5. Add the active damping term to V_{fpu} .
   6. Estimate the system states for (k + 1)
   7. Predict the system states for (k + 2).
   8. Evaluate cost function to define the optimum switching State (S opt), which will be applied in the next sampling period.

This research work uses the main advantages of FCS-MPC to improve the dynamic reactive power control of a HAPF. A discrete model based on LCL-Filter equations is used to predict the system behavior and optimize the cost function. Despite the similarity of mathematical model, the HAPF topology is quite different from a grid- connect converter with LCL-Filter. Therefore, it is not possible to assure convergence or proper operation of the algorithms the proposed topology using hybrid active power filter is as shown below



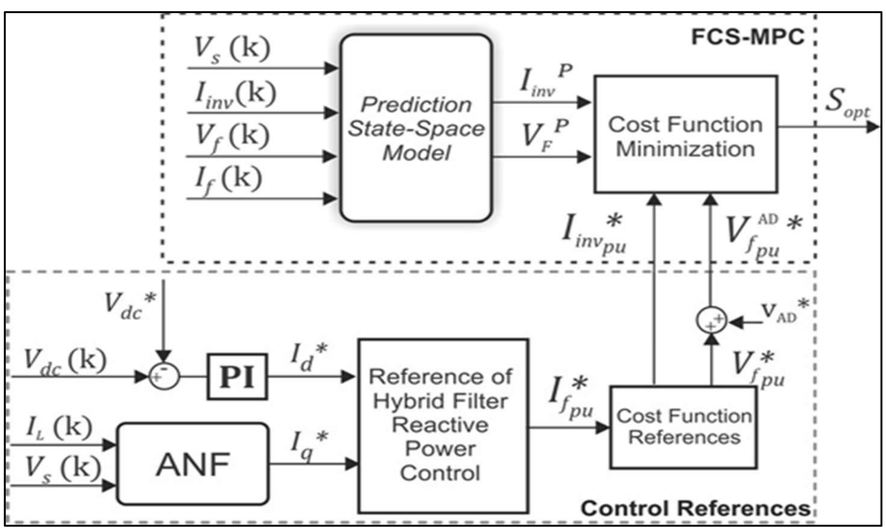
IMPLEMENTATION

Proposed Algorithm

The following step describes the proposed control:

1) Measure state variables: V_f, I_{inv}, If, V_s, I_L and V_{dc}.
2) Apply the optimum switching state S_{opt}.
3) Obtain the p.u. values of the system variables.
4) Estimate I_f^{q*} by applying the ANF to the load current.
5) Calculate the control references I_{fpu}^* , V_{fpu}^* , $I_{inv_{pu}}^*$
6) Add the active damping term to V_{fpu}^* .
7) Estimate the system states for (k + 1)
8) predict the system states for (k + 2).
9) Evaluate cost function to define the optimum switching state (S_{opt}), which will be Applied in the next sampling period.

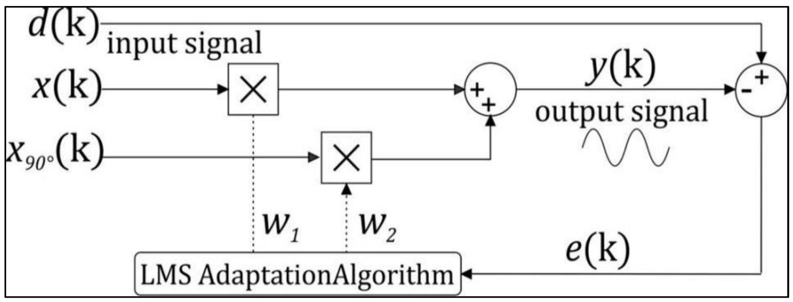
Proposed Block diagram of FCS-MPC applied to hybrid filter



Adaptive Notch Filter principle

The digital signal processing is the one of the fastest emerging and growing fields such as biomedical engineering, seismology, astrology, navigation, communication and control system operations in the last decades and it plays a major role in many application areas such as for reliability ,accuracy, small physical sizes and flexibility of the design constraint are considered. Adaptive system is a system whose coefficients could be automatically adjusted to changing environments and or an input signal. Adaptive Notch filters are used when there is uncertainty about the characteristics of the signal.

The use of FCS-MPC for controlling converters with LCL- Filter requires additional algorithms to avoid undesired resonances. This work applies an adaptive notch filter (ANF) for active damping and for obtaining the control references of the FCS-MPC. The ANF filter and its use in the proposed algorithms are explained in the following section. The below figure presents the ANF structure, In this case, d(k) is the input signal, y(k) is the output signal and the error e(k) is used in the adaptation law. The objective of this filter is to guarantee y(k) can track the fundamental frequency of input signal in amplitude and phase. The coefficient are adjusted using the least mean square(LMS) algorithm although the LMS is the simplest algorithm in adaptive filtering ,in presents similar for harmonic extraction when compared to the recursive least square algorithm (RLS).



The general recursion formula of LMS algorithm applied for the ANF is presented in the following way

$y(k) = w_1(k)x(k) + w_2(k)x_{90^0}(k)$ (11)

$e(k) = d(k) - y(k)$ (12)

$w_1(k + 1) = w_1(k) + \mu e(k)x(k)$ (13)

$w_2(k + 1) = w_2(k) + \mu e(k)x_{90^0}(k)$ (14)

Where x(k) and x_{90^0} (k) are two orthogonal signals provided by a digital PLL (Phase Locked Loop), w_1(k) and w_2 (k) are filter coefficients and μ is the step-size value. The parameter μ controls the algorithm rate of convergence and its accuracy. This ANF has only two coefficients to be adapted, which makes this configuration easier and faster when compared to others [4]. Just like synchronous reference frame (SRF), this structure can separate the fundamental active and reactive part of current (I^d and I^q) once the orthogonal signals x(k) and x_{90^0}(k) are in phase with the voltage source. For instance, consider the ANF output, which represents the fundamental component, given by:

$y(k) = w_1(k)\sin(wt) + w_2(k)\cos(wt)$ (15)

This component can be rewritten as:

$y(k) = A\sin(wt + \theta)$ (16)

Where, A is the peak value and θ is the angle between the reference and the output signal. Expanding this equation results in the following: $y(k) = A\cos\theta\sin(wt) + A\sin\theta\cos(wt) = w_1(k)\sin(wt) + w_2(k)\cos(wt)$ (17)

As a result, the ANF coefficients w_1(k) and w_2(k) are equivalent to the dq components in SRF, respectively. However, when compared to SRF, ANF has better dynamic response and shorter processing time

Adaptive Notch filter Control References

The HAPF model has three state variables related to the following considerations as explained below:

LCL Filter: $I_{f_{pu}}$, $V_{f_{pu}}$, and $I_{inv_{pu}}$ the reference $I^*_{f_{pu}}$directly controls the reactive power supplied by the equipment. However it is also possible to control HAPF reactive power indirectly by calculating the references of the $V^*_{f_{pu}}$and $I^*_{inv_{pu}}$ from $I^*_{f_{pu}}$ and the hybrid filter model equations can be designed as below as under

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i) Reference of Hybrid Filter Current (I_{fpu}^{d*})

The reference I_{fpu}^{*} directly controls the active and reactive power of the hybrid filter. The active power is controlled by I_{f}^{d*}, which is in phase with source voltage and is responsible for the DC link voltage regulation. The reactive power is controlled byI_{f}^{q*}, which is responsible for the dynamic reactive power control. So, $I_{fpu}^{*}$is composed as:

$I_{fpu}^{*} = I_{fpu}^{d*}\sin(wt) + I_{fpu}^{q*}\cos(wt)$ (18)

Where sin (wt) and cos (wt) are provided by a PLL in phase with source voltage.

Current I_{fpu}^{d*} is obtained by a PI controller, which aims to maintain the DC link voltage at its reference value. On the other hand, current I_{fpu}^{q*} has to track the load reactive power variations. The ANF is applied to the load current and provides the reactive reference of the HAPF, in a way that $I_{fpu}^{q*}=w_1^{I_L}$. The coefficients $w_1^{I_L}$ and $w_2^{I_L}$ are the ANF coefficients for the load current

2) Reference of LCL-Filter Capacitor Voltage (V_{fpu}^{*})

The reference of LCL -Filter voltage (V_{fpu}^{*}) is calculated by the following equation in dq reference frame:

$$V_{fpu}^{dq}=V_{s_{pu}}^{dq}-(R_{pu}+jX_{pu})I_{fpu}^{dq} \quad (19)$$

Where, R_{pu} is the equivalent resistance of the hybrid branch, and is composed by the transformer resistance ($R_{t_{pu}}$) and the capacitor bank resistance ($R_{c_{pu}}$), then, $R_{pu}= R_{t_{pu}}+R_{c_{pu}}$. Likewise, $X_{pu}$is the equivalent reactance of the hybrid branch and is composed by the inductive reactance of the transformer ($X_{t_{pu}}$) and the capacitive reactance of the capacitor bank ($X_{c_{pu}}$), in a way such that

$X_{pu} = X_{t_{pu}} - X_{c_{pu}}$

For calculating $V_{f_{pu}}^{*}$ from (18), it is necessary to replace $I_{f_{pu}}^{dq}$ by$I_{f_{pu}}^{dq*}$. Next, the $V_{s_{pu}}^{dq}$ values can be obtained by using an ANF in the measured source voltage, resulting in:

$$\begin{bmatrix} V_{fpu}^{d*} \\ V_{fpu}^{q*} \end{bmatrix} = \begin{bmatrix} V_{spu}^{d} \\ V_{spu}^{q} \end{bmatrix} + \begin{bmatrix} -R_{pu} & X_{pu} \\ -X_{pu} & -R_{pu} \end{bmatrix} \begin{bmatrix} I_{fpu}^{d*} \\ I_{fpu}^{q*} \end{bmatrix} \quad (20)$$

The ANF estimates the fundamental value of voltage, and its coefficients provide the required information, so that: $V_{s_{pu}}^{d} = w_1^{V_s}$ and: $V_{s_{pu}}^{q} = w_2^{V_s}$. Here, $w_1^{V_s}$ and $w_2^{V_s}$ are the ANF coefficients for source voltage. Finally, the reference of LCL filter capacitor voltage is given by:

$V_{f_{pu}}^{*} = V_f^{d*}\sin(wt) + V_f^{q*}\cos(wt)$ (21)

3) Reference of Inverter Current ($I_{inv_{pu}}^{*}$)

The reference of Inverter Current ($I_{inv_{pu}}^{*}$) is obtained based on the following equation:

$V_{f_{pu}}^{dq} = (R_{cf} - jX_{cf_{pu}})(I_{f_{pu}}^{dq} - I_{inv_{pu}}^{dq})$ (22)

As $X_{cf} >> R_{cf}$ in fundamental frequency, so the capacitor resistance can be disregarded. For calculating $I_{inv_{pu}}^{dq*}$ the reference values obtained in previous sessions, $V_{f_{pu}}^{dq}$ and $I_{f_{pu}}^{dq*}$, are replaced in (22), resulting in:

$$\begin{bmatrix} I_{inv_{pu}}^{d*} \\ I_{inv_{pu}}^{q*} \end{bmatrix} = \begin{bmatrix} I_{fpu}^{d*} \\ I_{fpu}^{q*} \end{bmatrix} + \begin{bmatrix} \frac{1}{X_{cf_{pu}}} \\ -\frac{1}{X_{cf_{pu}}} \end{bmatrix} \begin{bmatrix} V_{fpu}^{d*} \\ V_{fpu}^{q*} \end{bmatrix} \quad (23)$$

In time domain, current is given by:

$$I^{*}_{inv_{pu}} = I^{d*}_{inv_{pu}} \sin(wt) + I^{q*}_{inv_{pu}} \cos(wt) \qquad (24)$$

RESULTS AND DISCUSSION

Performance of MPC Controller and HAPF

The main objective of this project is to design a control strategy so that the controller can inject a suitable level of voltage depending upon the variations that exist on the load side of the power system when the variations are more serious load side which may prevent the uncertainty and instability of economic operation of power system. The another feature of FCS-MPC controller is that the FCS-MPC controller decouples active and reactive power flow (constant dc link voltage) and can follow the fluctuation in current reference accurately. The another added feature of the FCS-MPC controller is that it achieves the fast compensation in order to avoid voltage fluctuations, guarantee minimum line current and properly track the load reactive power.

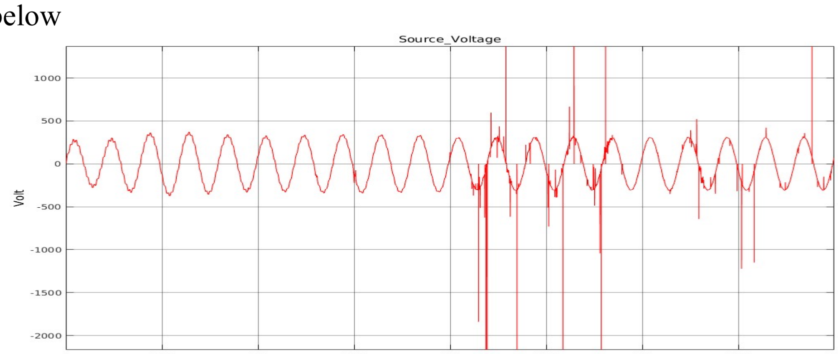
The Hybrid active power filter (HAPF) assures the reactive power control by assuring zero reactive power at the source and hence the total harmonic distortion (THD) of the hybrid filter current source is normally less than 5%.

Proposed Simulation Design with FCS-MPC Controller

The proposed simulation model is implemented in MatlabR20916a Simulink software, and is designed in various stages from source side to load side along with linear load and non linear load with proposed FCS-MPC controller design method further,this design implementation also involves design consideration of total harmonic distortion reduction (THD) as explained below:

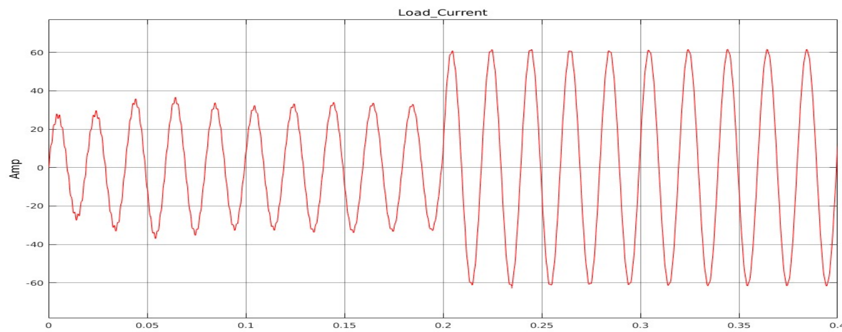
a) Source Side

The generated voltage is usually sinusoidal in nature and consists of continuous variations as per the load requirements of load such as linear and nonlinear type loads. The below graph shows nature of source voltage which is almost constant magnitude and direction depending upon set value of time duration for which load happens to change. Initially the source voltage remains constant for a nonlinear load for a duration upto 0.2 seconds, then when suddenly load changes to linear type their exists fluctuation’s in the magnitude of source voltage due to presence of harmonics present in the variations of source voltages which is indicated by distorted sinusoidal waveforms. This is represented by the same wave but after the duration of 0.2 seconds as below



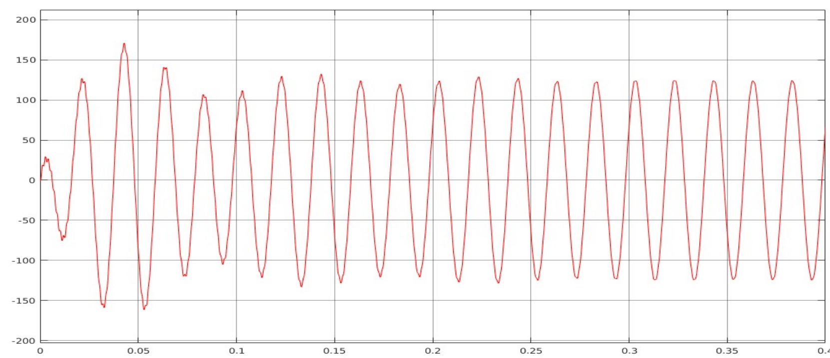
b) Load Side

The main implementation of the project is the part of design of controller towards load side for injecting the requirement voltage which is necessary for injecting into the controller so that given load when switching into linear type load requires an inclusion of injecting inverter voltage current so as to compensate towards the existing harmonics, distortions present during the change of load voltage side. As seen from below graph the load current remains unvarying during duration till 0.2 seconds but when the load currents changes into nonlinear load the load current is also nonlinear due to distortion presence, but with inclusion of inverter injection the magnitude of load current is compensated this exists for duration after 0.2 seconds to 0.4 seconds.



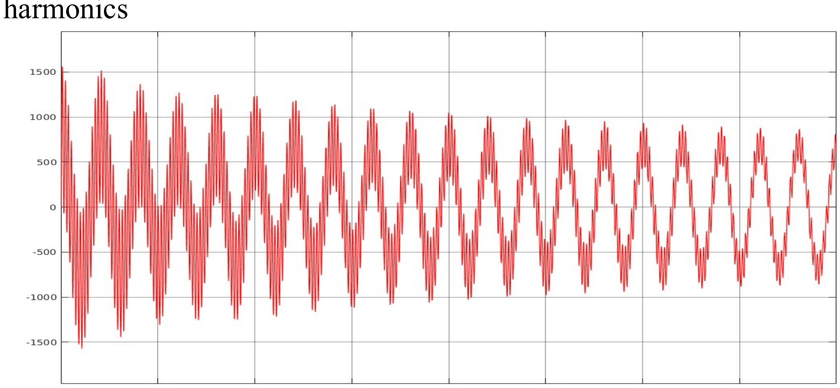
c) Source Voltage after Injection

The method of using this project implementation helps in designing and maintaining a constant stabilized output voltage after successful injection by the designed inverter using FCS-MPC controller. As per our design methodology, As indicated in the below graph the normalized voltage do exists for nonlinear type load as below for all durations starting from origin itself irrespective of load variations during nonlinear and linear switching actions.



d) Variations of distortions due to Injected Voltage

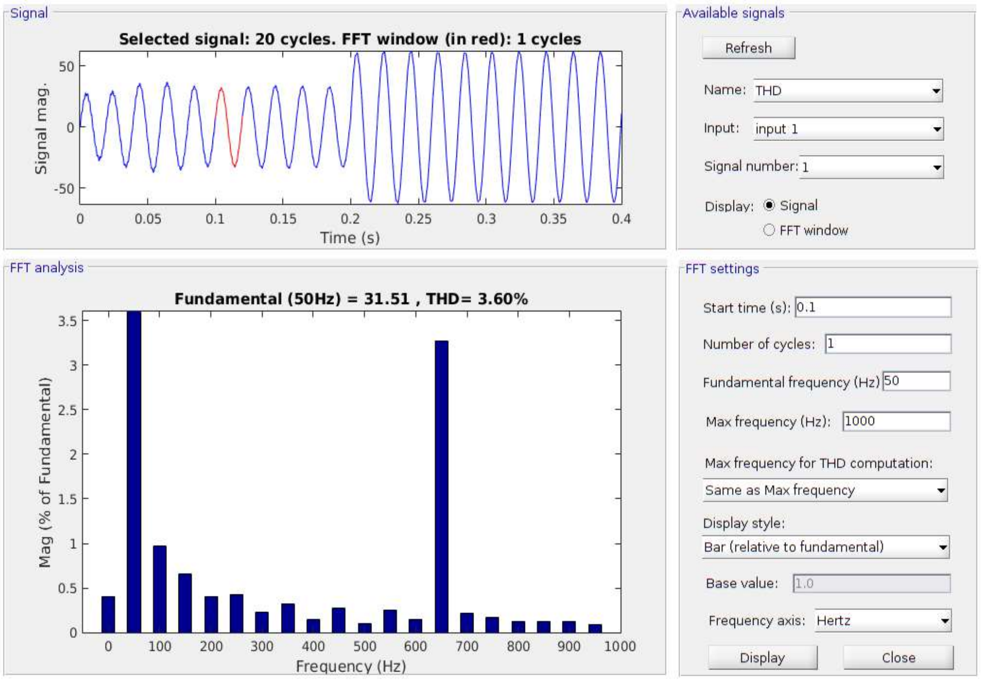
The main aspect of this project is to enable design a control strategy such that the power system can be operated efficiently and reliably suiting such that the controller can take corrective action such that there may not be reductions in the level of voltages due to variation s of varying load towards source or load side. The below graph analysis conclude that there exists harmonic distortions for a nonlinear load type initially for 0.2 seconds but when load changes to linear type the distortions can be minimized by injecting voltage compensating the harmonics



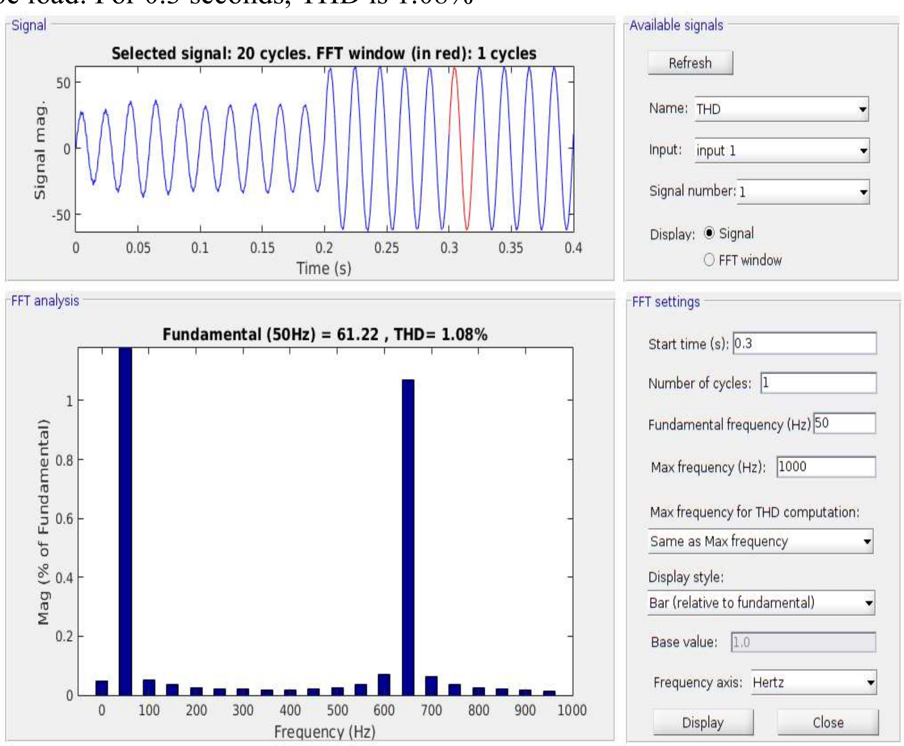
e) FFT Analysis Graph

A THD block is the computing block that computes the total harmonic distortion of a periodic distorted signal due to voltage or current present in it. An Ideal value of THD block should have less than 5% of value of THD. As shown in below graph consisting of nonlinear type and linear type are as seen below.

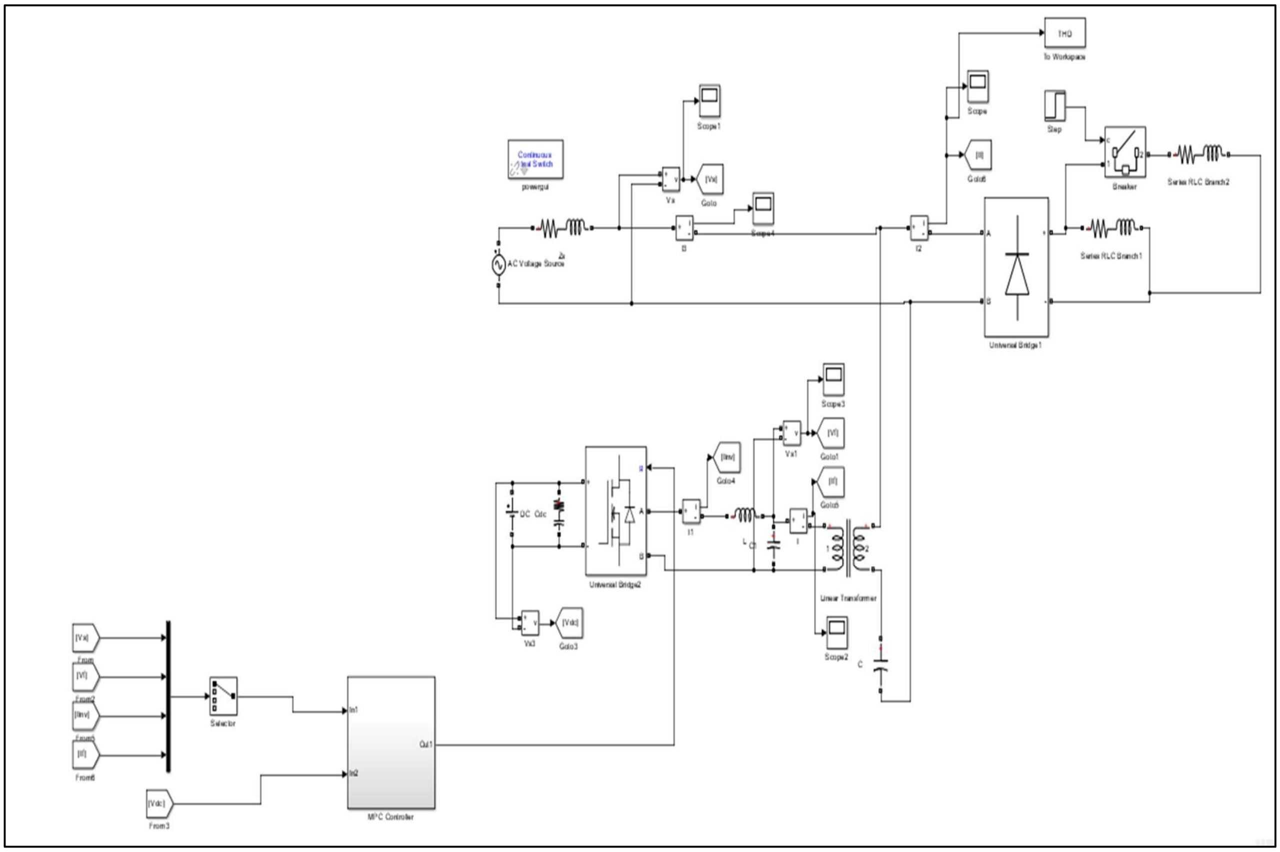
i) For Non Linear type load: For 0.1 seconds, THD is 3.60%



ii) For Linear type load: For 0.3 seconds, THD is 1.08%



f) Proposed design Implementation using Matlab Simulink



CONCLUSION

The application of FCS-MPC in the hybrid active power filter will be implemented in this project. The algorithm was able to control the HAPF reactive power, improve it dynamic response, decouple the active and reactive power control and track fluctuating references of reactive power. It was demonstrated the inverter current control is not enough to guarantee proper operation of the FCS-MPC algorithm. An adaptive notch filter is used to implement the active damping and harmonic blocking algorithm. It assures adequate THD of hybrid filter current in steady-state. As a result, the presented control strategy based on FCS-MPC and adaptive filters can be considered as an alternative to classical reactive power control.

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