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Research Article

Unknown input observer-Model predictive control scheme for state and disturbance estimation of shunt active filter

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Abstract:

The distribution system's nonlinear loads cause low total harmonic distortion (THD), low distortion power factor, and localized communication interference, among other poor power quality metrics. Shunt active power filter (SAPF) capacity to function depends on the controller's ability to follow the reference signal. To manage larger systems with several inputs and outputs, it would be challenging task to design PID controllers, because excessive controller gains would need to be tuned. Also, every control loop would operate independently of one another, as if there were no interactions between the two loops. This paper proffers Model prediction control for Shunt active power filter (SAPF), which can manage systems with several inputs and outputs that may interact with one another. Luenberger observer (LO) and Proportional Integral observer (PIO) fail to estimates the actual states of SAPF to SAPF, as shown even in the presence of three unknown disturbances, i.e step, triangular and noise type. The proposed unknown input observer (UIO) in the presence of three unknown disturbances perfectly tracks the reference signal. Apart from state estimation, the proposed observer also estimates all the unknown disturbances, when compared to PIO. The results have been simulated in MATLAB environment.

1. Introduction

In recent decades, the application of loads, which are not linear, draw currents which are not sinusoidal has increased. The primary source of harmonics that degrade system power quality is these nonlinear loads [1-3]. Historically, power quality issues were resolved with passive filters [4]. Unfortunately, passive filters are limited to filtering the frequencies for which they were designed and have a hefty shape. An appealing way to enhance the power quality of an electrical network is to use a shunt active power filter (SAPF) [5]. Among SAPF's advantages are its small size, adaptability, and superior filtering capabilities. The SAPF is typically a three-phase voltage source inverter with current control, and an AC side filter inductor interface and a DC side storage capacitor. The SAPF serves as a source of current, injecting the reactive power and current harmonics necessary for the load to provide clean sinusoidal waveforms and balanced, three-phase supply currents. The two main ways that the SAPF functions are the production of reference currents and the current control mechanism, which involves tracking the reference currents. Among the techniques that have been presented in the literature, Hysteresis, linear pulse width modulation (PWM), and deadbeat current control techniques are the most often used methods for tracking current [6]. A hysteresis band controller manages the current error in a nonlinear current control method called hysteresis. When an inaccuracy in current crosses a certain band, switching signals are altered. However, good current monitoring requires a small hysteresis band, which raises the switching frequency. PWM is a linear control method that generates the reference voltage signals using a proportional-integral (PI) controller. After that, a modulating stage is needed to provide the necessary gating signals, either using space vector modulation (SVM) or carrier triangular waveforms. However, because of the large frequency range of the harmonic content, PI control in the stationary reference frame leads to an inadequate, sluggish response with poor tracking capacity [7]. Deadbeat current control involves replacing the PI controller with a deadbeat controller. This produces the voltage vector required to deliver zero current error at the next sampling point. On the other hand, the deadbeat controller is greatly impacted by system parameter instability, noise in monitored signals, and computation delays that need an excessively high sampling frequency [8]. Conversely, for high-power applications, the SAPF control method needs to meet requirements such as extremely high dynamics, precision in the production of compensating currents, or switching-frequency reduction. Regretfully, sampling frequency has a significant impact on the dynamics of the widely employed proportional-integral (PI) controller for current regulation, which inevitably results in a bandwidth limitation of SAPF control response. The alternative method, delta-modulation or basic digital-hysteresis controllers [9,10], provides an instantaneous reaction, but it becomes challenging to construct output passive filters with a variable and high switching frequency [11,12].

These drawbacks of traditional control methods led to the development of finite control set model predictive control as a superior control substitute [13]. Due to its many advantages, including its ability to incorporate system nonlinearities and limitations into the controller with ease and its quick tracking response, Model Predictive management (MPC) has gained popularity in the management of power electronics converters [14,15]. MPC uses a cost function minimization process to determine the optimal control action by taking into account the system model and forecasting its future behaviour.

2. Material and Methods

Mathematical Modelling Of Shunt Active Filter

The dynamics of SAPF-Multi Input Multi Output (MIMO) can be represented in the form of three state variable equations as described below.

$$\frac{di_d}{dt} = -\frac{R_f}{L_f} i_d + \omega i_q - \frac{d_d}{L_f} V_{dc} + \frac{1}{L_f}\vartheta \quad (1)$$

$$\frac{di_q}{dt} = -\frac{R_f}{L_f} i_q + \omega i_d - \frac{d_q}{L_f} V_{dc} \quad (2)$$

$$\frac{dV_{dc}}{dt} = \frac{3}{2C_f}\left(d_d i_d + d_q i_q\right) \quad (3)$$

where i_d, i_q are d-q axis currents, R_f is the total losses in coupling resistance and inverter, L_f is leakage inductance of the coupling inductor, d_d and d_q are d-q axis control inputs, V_{dc} represents DC-link voltage, C_f represents DC bus capacitor. The state vector $x = \left[i_d \;\; i_q \;\; V_{dc}\right]^T$ represents state, and control input vector $u = [d_d \;\; d_q]^T$ represents respectively, and ϑ represents fault. The dq-frame rotates with an angle $\theta = \omega t$ from the reference axis of abc-frame. State space equation of SAPF can be written as

$$\dot{x} = Ax + Bu + Ev$$

where, $x \in \mathbb{R}^3 = [i_d \quad i_q \quad V_{dc}]^T$,

$u \in \mathbb{R}^2 = [d_d \quad d_q]^T$ and $v \in \mathbb{R}^1$

$$A = \begin{bmatrix} -\frac{R_f}{L_f} & \omega & -\frac{d_d}{L_f} \\ -\omega & -\frac{R_f}{L_f} & \frac{-d_q}{L_f} \\ \frac{3D_d}{2C_f} & \frac{3D_q}{2C_f} & 0 \end{bmatrix} \quad B = \begin{bmatrix} \frac{V_{dc}}{L_f} & 0 \\ 0 & \frac{V_{dc}}{L_f} \\ \frac{3\, I_d}{2C_f} & \frac{3\, I_q}{2C_f} \end{bmatrix}$$

$$\text{and } E = \begin{bmatrix} \frac{1}{L_f} & 0 & 0 \end{bmatrix}^T$$

Model predictive control

MPC is a method of feedback control that prophesy a process's future output by using a model. MPC has the advantage of being a multi-variable controller, meaning it considers all interactions between system variables and regulates the output concurrently as shown in Figure 1. The ability of MPC to work with limits is another of its strengths. Limitations are crucial since going against them might have unfavorable effects. For instance, following speed restrictions and keeping a safe distance from other vehicles are two driving safety requirements. Other restrictions, such acceleration limits, are a result of the physical constraints of the automobile. If this were an autonomous vehicle under MPC control, the controller would meet each of these restrictions and track a desired course.

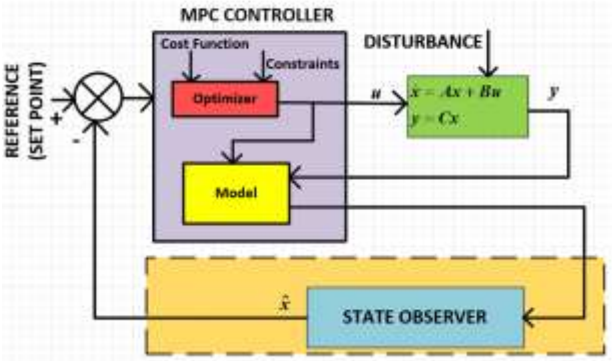

Figure 1. *General Block Diagram of Model Predictive Control*

Additionally, MPC has a preview option that functions similarly to feedforward control. An autonomous vehicle, for instance, drives on a curved road. It can only apply brakes while navigating a turn if it is unaware that one is approaching. The controller will be aware of an approaching turn ahead of time, allowing it to apply the brakes more quickly and safely stay in the lane, if the vehicle is equipped with a front-facing camera that captures data on the path the car will travel. MPC may easily incorporate future reference information into control issues to improve controller performance. Since the 1980s, MPC has been utilized in the process sector. Microprocessors are being used in more industries due to their rising computational capacity. Despite all of these benefits, MPC requires a powerful, fast CPU and a large amount of RAM, and the explanation for this is because every time interval, MPC finds a solution to an online optimization problem.

Design parameters

Selecting the right settings for these parameters is crucial because they impact at each step, the computational expense of MPC method, which deciphers an online optimization issue, as well as performance of controller. Sample time, prediction horizon, control horizon, constraints, and weights are some of these factors.

Sample time

By choosing the sample time, we may choose the speed at which the controller performs the control algorithm. If the disturbance is too large, the controller won't be able to respond to it quickly enough.

In contrast, the controller can respond to disturbances and set point changes considerably more quickly if the sample period is too short, but this results in an excessive computing burden. To find the best trade-off between computational effort and performance, fitting ten to twenty samples within the open loop response's rising time is advised.

Prediction horizon

As previously stated, in order to push plant output as near to the set point as is practicable, the optimizer selects the best order of control inputs. At every time step, the MPC controller forecasts the plant's future output. The controller's prediction range is shown by the number of predicted horizons. What occurs if it isn't long enough?

Consider the example that follows. You know that using the brakes will take five seconds to bring your automobile to a stop while you're traveling at fifty miles per hour. It will be too late to apply the brakes when you notice the traffic lights if your prediction horizon is two seconds. The vehicle can only come to a stop after navigating through the traffic signals. Thus, we ought to pick a prediction horizon that encompasses the important system dynamics. Twenty to thirty samples encompassing the open-loop transient system response are advised for selecting the prediction horizon.

Control horizon

The control horizon is another component in design. Each control move on the control horizon may be viewed as a free variable that the optimizer must determine if this is the set of future control actions that will result in the anticipated plant output. Therefore, there are fewer computations the smaller the control horizon. Then, why don't we select a control horizon of 1 for every instance? We could, but it could not provide us with the most advantageous move. Moreover, we can improve our forecasts by extending the control horizon, but doing so would make things more complicated. It is also possible to decide to set the control horizon to match the forecast horizon. But one need to keep in mind that the remaining control changes often have a little impact on the expected output behavior, whereas the initial steps typically have a significant impact. Consequently, selecting a very wide control horizon becomes more difficult and necessitates two or three steps.

3.1.4 Constraints

MPC may be used to integrate constraints on inputs, outputs, and the rate of change of the inputs. These restrictions might be strong or mild. While soft restrictions are more flexible, hard constraints are unbreakable. Assume that this car's speed is managed by an MPC controller through adjustments to the gas pedal. We want to establish a hard constraint to ensure that the gas pedal position stays within this range because there is a physical limit to how far it can be adjusted. We could also wish to require maintaining a speed that falls within specific values. On the other hand, it is not a good idea to impose strict limits on both inputs and outputs as they might clash and make the optimization issue unsolvable. Therefore, the optimizer will not be able to identify a workable solution that satisfies both input and output constraints if the speed requirement is severe. If the speed restriction is soft, on the other hand, the controller will permit exceeding it up until the vehicle clears the slope, preventing a dispute from arising. Observe that the optimization challenge is minimizing the violation of the soft constraint in order to keep it small. It is advised to create soft output limitations rather than strong constraints on the inputs or the pace at which the inputs change.

Weights

While maintaining smooth control movements to prevent forceful control maneuvers, we also want the outputs to track as closely as feasible to their setpoints. Weighing the input rates and outputs in relation to one another can help you attain a balanced performance between these conflicting aims. In addition to adjusting the relative weights inside the groups, we additionally weigh these two groups in relation to one another.

3. Results and Discussions

Simulation Results

When compared to compared to classical conventional State feedback (SFB) and Linear Quadratic Regulator (LQR) control strategies, MPC control technique has fast dynamics, which is shown in Figure 2.

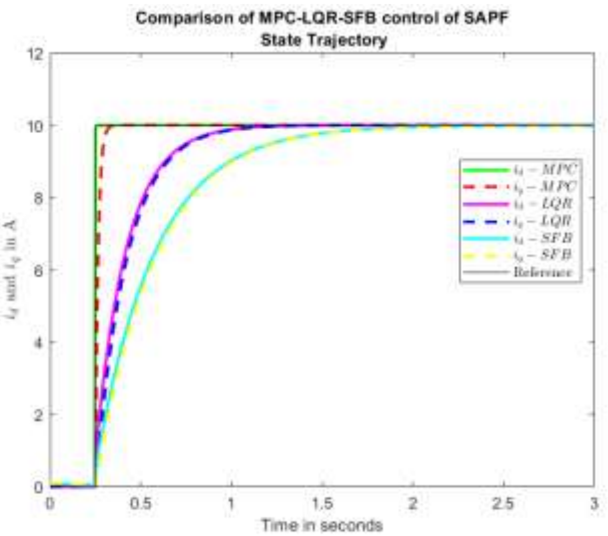

Figure 2. *State estimation of MPC-LQR-SFB based control of SAPF*

The simulation results of MPC based control of SAPF with LO, PIO and UIO in presence of three unknown disturbances are shown in Figure 2.

MPC driven of SAPF with LO, PIO and UIO in presence of unknown sinusoidal disturbance (Step reference). The state estimation simulation results of MPC based control of SAPF with LO, PIO and UIO in the presence of unknown sinusoidal disturbance is shown in Figure 3. It can be observed that both first, second states as well as their estimated states of SAPF with LO and PIO are unable to track step reference input, in the presence of unknown sinusoidal disturbance. The error plots of LO and PIO-based control of SAPF are also shown, which indicates that there exists a steady state error in the presence of unknown sinusoidal disturbance. On the other hand, both first, second states as well as their estimated states of SAPF with UIO tracks perfectly the step reference input, in the presence of unknown sinusoidal disturbance. The step input is given at 0.25 seconds and unknown sinusoidal disturbance is given at 0.75 seconds. The error plots of UIO-based control of SAPF are also shown, which indicates that there no steady state error in the presence of unknown sinusoidal disturbance.

The unknown sinusoidal disturbance estimation of PIO and UIO based MPC control of SAPF is shown in Figure 4. It can be observed that UIO perfectly tracks the actual unknown sinusoidal disturbance when compared to PIO. MPC driven of SAPF with LO, PIO and UIO in presence of unknown triangular disturbance (Step reference).

The state estimation simulation results of MPC based control of SAPF with LO, PIO and UIO in the presence of unknown triangular disturbance is shown in Figure 5. It can be observed that both first, second states as well as their estimated states of SAPF with LO and PIO are unable to track step reference input, in the presence of unknown triangular disturbance. The error plots of LO and PIO-based control of SAPF are also shown, which indicates that there exists a steady state error in the presence of unknown triangular disturbance. On the other hand, both first, second states as well as their estimated states of SAPF with UIO tracks perfectly the step reference input, in the presence of unknown triangular disturbance. The step input is given at 0.25 seconds and unknown triangular disturbance is given at 0.75 seconds. The error plots of UIO-based control of SAPF are also shown, which indicates that there no steady state error in the presence of unknown triangular disturbance.

The unknown triangular disturbance estimation of PIO and UIO based MPC control of SAPF is shown in Figure 6. It can be observed that UIO perfectly tracks the actual unknown triangular disturbance when compared to PIO. MPC driven of SAPF with LO, PIO and UIO in presence of unknown noise-type disturbance (Step reference)

The state estimation simulation results of MPC based control of SAPF with LO, PIO and UIO in the presence of unknown noise-type disturbance is shown in Figure 7. It can be observed that both first, second states as well as their estimated states of SAPF with LO and PIO are unable to track step reference input, in the presence of unknown noise type disturbance. The error plots of LO and PIO-based control of SAPF are also shown, which indicates that there exists a steady state error in the presence of unknown noise type disturbance. On the other hand, both first, second states as well as their estimated states of SAPF with UIO tracks perfectly the step reference input, in the presence of unknown noise type disturbance. The step input is given at 0.25 seconds and unknown noise type disturbance is given at 0.75 seconds. The error plots of UIO-based control of SAPF are also shown, which indicates that there no steady state error in the presence of unknown noise type disturbance.

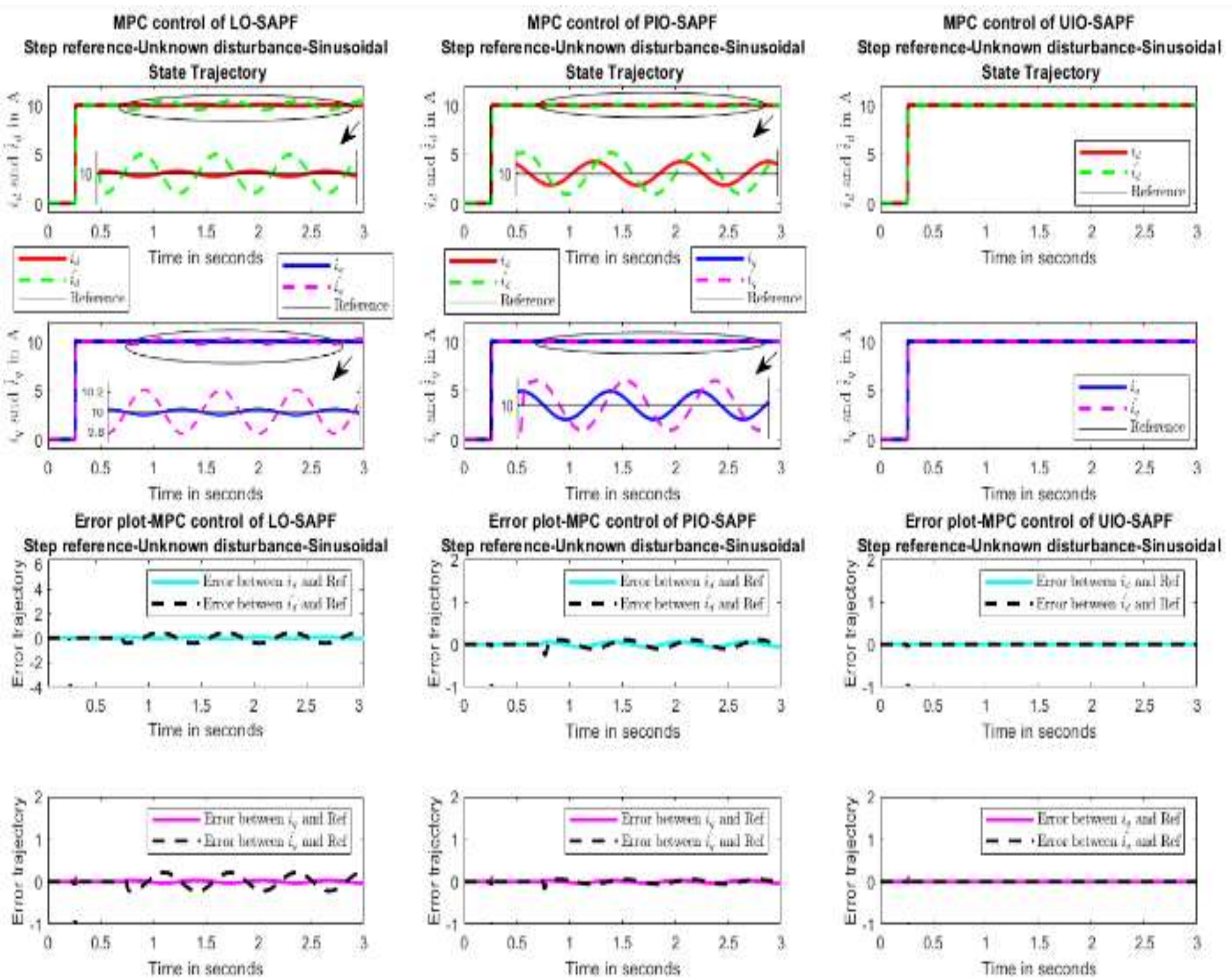

Figure 3. *State estimation of MPC based control of SAPF with LO, PIO and UIO in presence unknown sinusoidal disturbance*

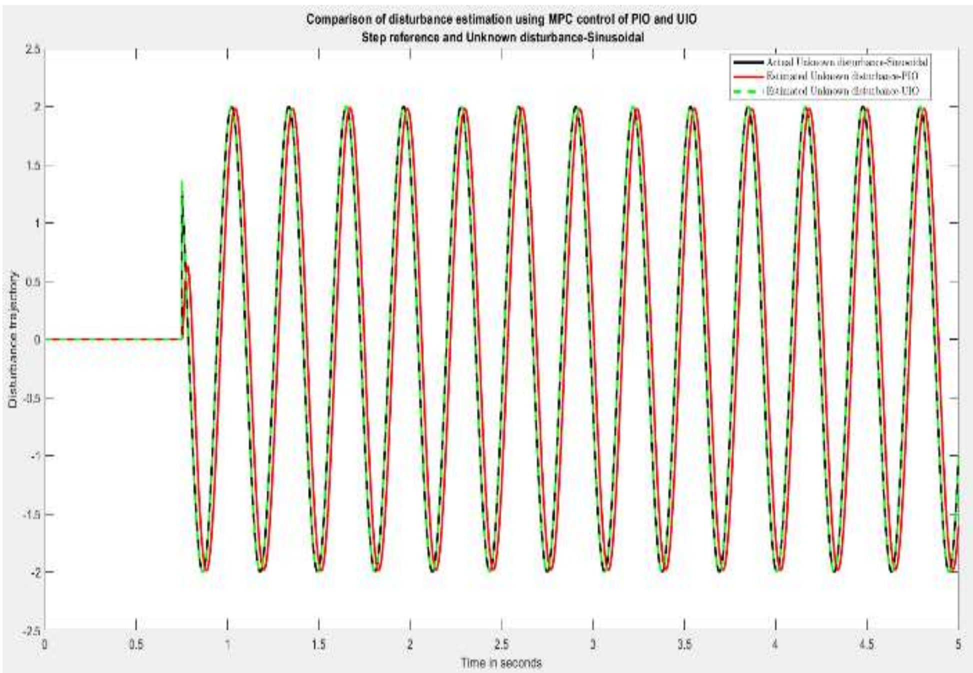

Figure 4. *Disturbance estimation of MPC based control of SAPF with LO, PIO and UIO in the presence of unknown sinusoidal disturbance*

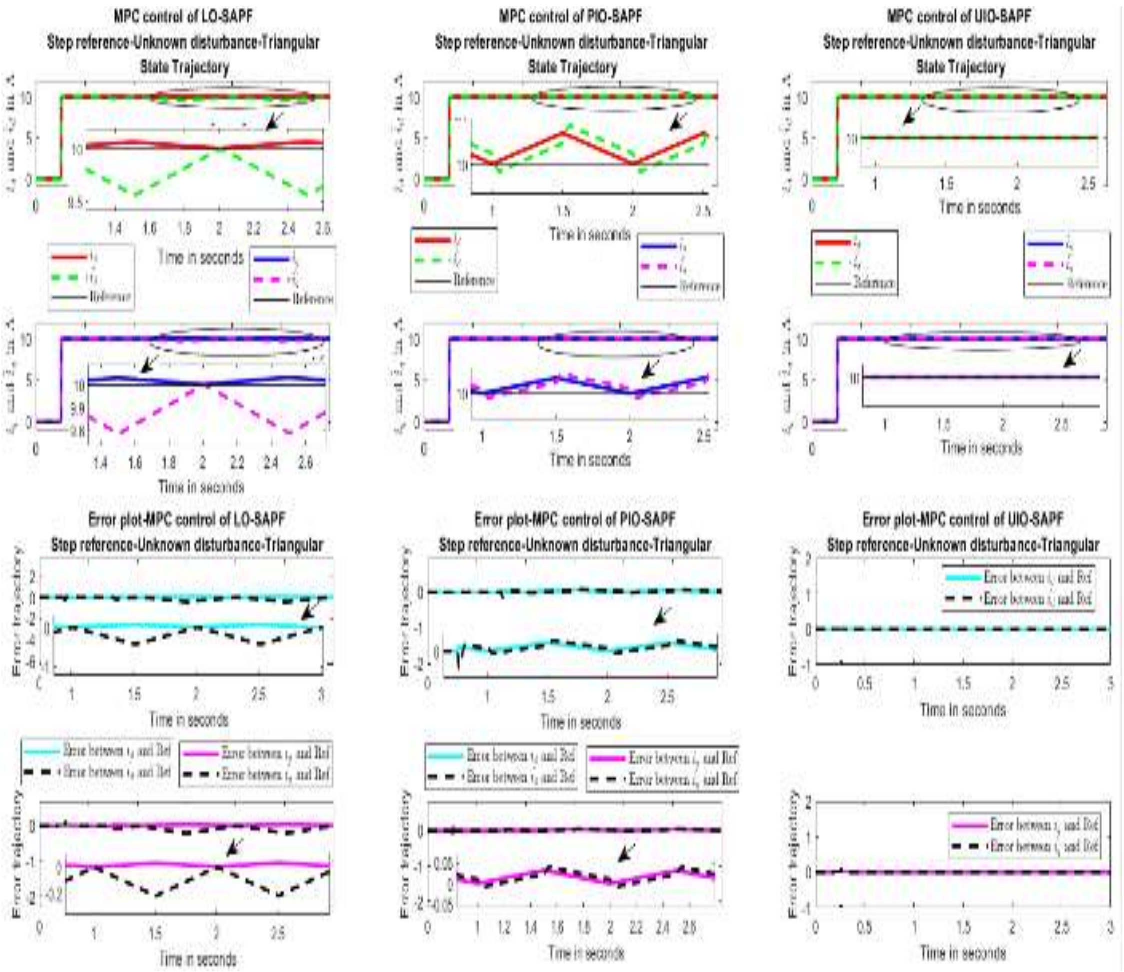

Figure 5. *State estimation of MPC based control of SAPF with LO, PIO and UIO in the presence of unknown triangular disturbance*

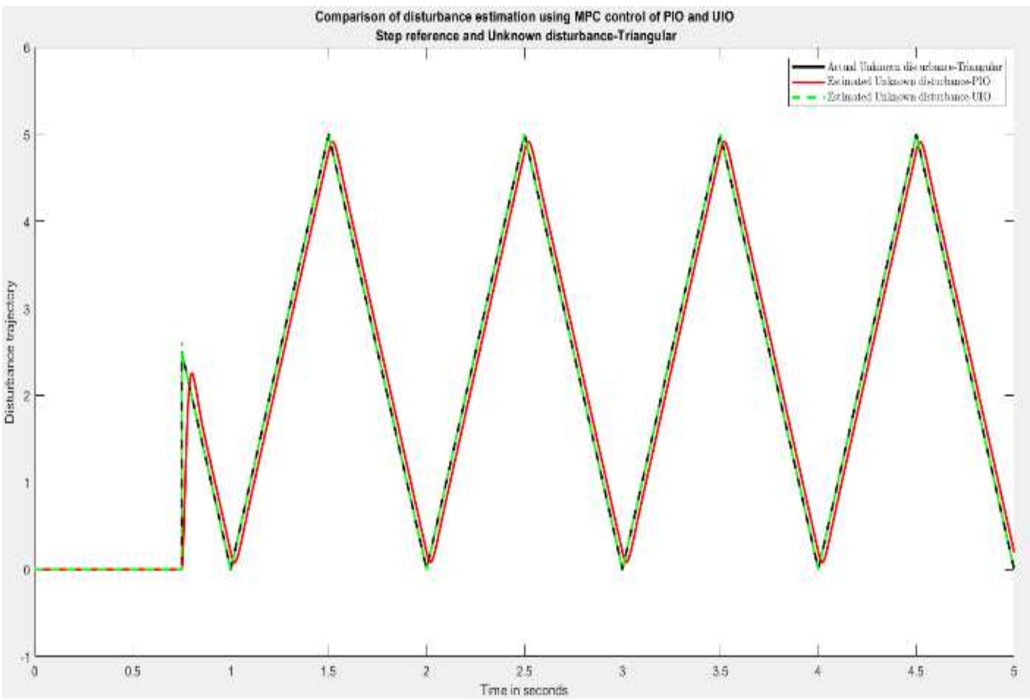

Figure 6. *Disturbance estimation of MPC based control of SAPF with LO, PIO and UIO in the presence of unknown triangular disturbance*

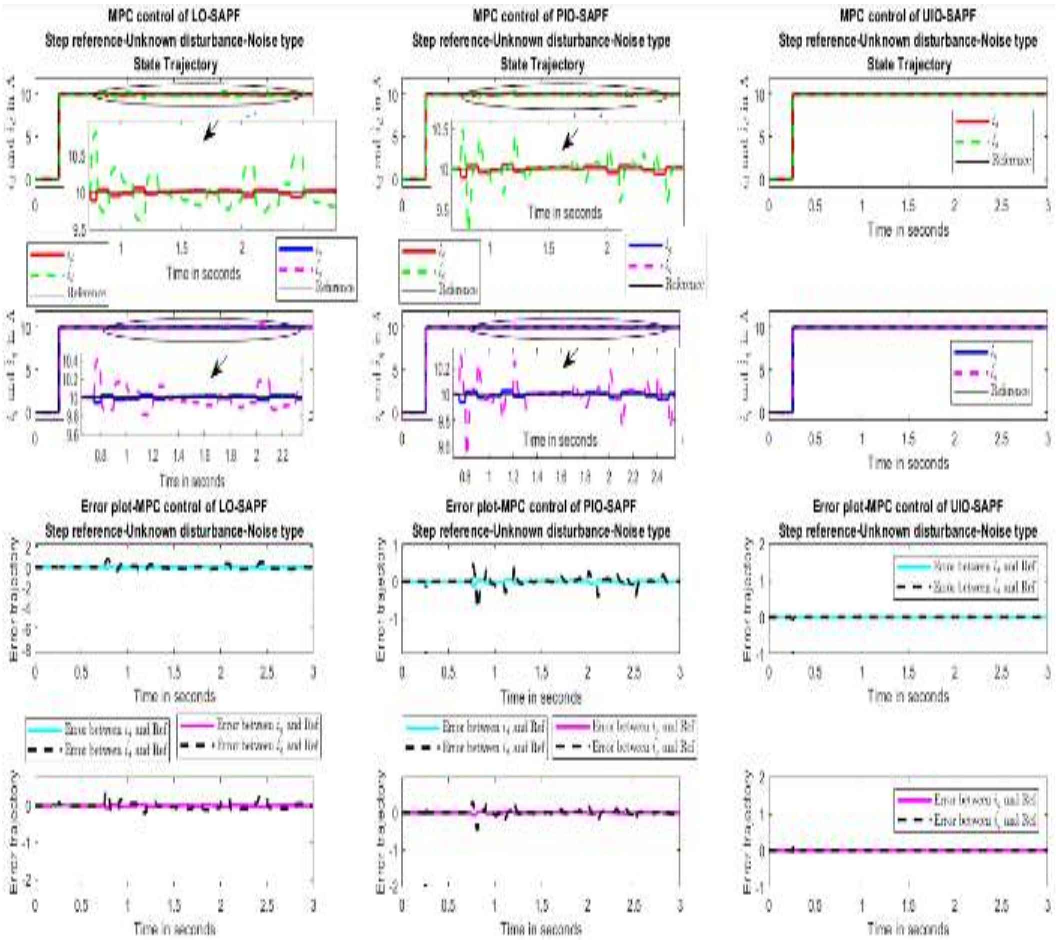

Figure 7. *Disturbance estimation of MPC based control of SAPF with LO, PIO and UIO in the presence unknown noise type disturbance.*

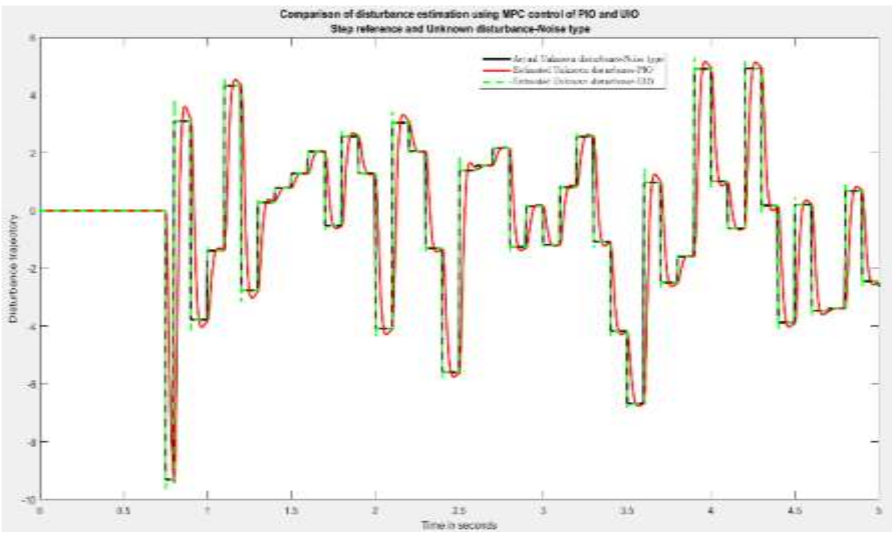

Figure 8. *Disturbance estimation of MPC based control of SAPF with LO, PIO and UIO in the presence of unknown noise type disturbance*

The unknown noise type disturbance estimation of PIO and UIO based MPC control of SAPF is shown in Figure 8. It can be observed that UIO perfectly tracks the actual unknown noise type disturbance when compared to PIO.

4. Conclusions

This paper proposed model predictive control-unknown input observer scheme for estimating the actual states and disturbance as well in the presence of three unknown disturbances. It has been effectively proved through simulation results that SAPF with LO and PIO, the actual states and their estimates failed to track the reference signal. On the other hand, SAPF with UIO, the actual states and their estimates perfectly tracks the reference signal. SAPF with both PIO and UIO have estimated the three unknown disturbances. Among them, UIO estimates perfectly all three unknown disturbances when compared to PIO.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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