# Dynamic Control Design for UPFC using Model Predictive Control

A. HAIDER, S.A. Al-MAWSAWI, Q. ALFARIS
Department of Electrical and Electronic Engineering
College of Engineering
University of Bahrain
Isa Town, P.O. Box 32038
KINGDOM OF BAHRAIN
aakbar@uob.edu.bh, aalmossawi@uob.edu.bh, qalfares@hotmail.com

***Abstract:*** Flexible AC Transmission System (FACTS) technology is one of the innovative solutions which were proposed to obtain better utilization and controlling of power over the transmission network in steady state and transient conditions. Unified Power Flow Controller (UPFC) is selected in this study as it is considered as the most of powerful controller among all FACTS controllers. It has the capability of controlling concurrently or selectivity the transmission line parameters such as the voltage magnitude, impedance and phase angle, or alternatively the flow of the active and reactive power in the transmission line. The controllers which are being used in UPFC are very important to control the transmission lines parameters as desired and the type of these controllers is mainly conventional PI controllers. The main challenge of this type of controller is that the coefficients of the PI controller can't be modified automatically without intervention to cater any unforeseen change in the system. In this paper, the conventional PI controller used in the UPFC will be compared with an adaptive control scheme called Model Productive Controller (MPC). This type of adaptive controller which is connected to UPFC will be investigated to ensure its robustness, effectiveness and the capability to accommodate any sudden load change in the system of Single Machine to Infinite Bus (SMIB).

*Key-Words:* - FACTS, UPFC, MPC, ANN, SMIB

## 1 Introduction

FACTS Over the past years, it has been clearly noticed that the power demand has undergone a rapid growth worldwide due to increase in the rate of population and industrial growth and consequently the need of electric power. Accordingly, power grids are undergoing a significant evolution in generation, transmission and distribution systems. So, there will be a need to maximize the efficiency of generation, transmission and distribution of electric power and adding new lines to the new power plants in order to meet the load growth and electric market demands. Therefore, these challenges along with a rapid load growth and system complexity introduced the need of new technology called as FACTS, which considered as an important and effective option to increase the controllability and optimize the existing power capacity through the use of power electronic devices. UPFC which will be studied in this paper is considered as one of the most important device in the FACTs devices family. It can control, independently or simultaneously, all parameters that affect the active and reactive power flow on the transmission line such as the voltage magnitude, impedance and phase angle. Moreover, the controllers which are being used in UPFC are very important to control all those parameters as desired. The conventional PI controller being used in UPFC application has a challenge to solve the system problem during system disturbance and sudden load change. Accordingly, this type of controller will be compared with the adaptive scheme called Model Predictive Controller. MPC considered as an effective solution for improving the system oscillation in single machine to infinite bus and improve the system stability. Moreover, MPC can provide a streamlined solution for solving Multi-Input Multi-Output control problems that are subject to constrains in the system and has the influence in the instantaneous as well as future performance of the dynamic system [1]. The earlier MPC challenges were the cost of software development and memory to perform the system identification of the plant to design MPC.

In 1970's, engineering at Shell Oil introduced their own MPC technology with an initial application in 1973 [2]. A comprehensive study of self-adaptive long range predictive control methods was introduced by R.M.C.De Keyser et. al. (1988) [3]. For the selection of predication horizon, R. Scattolini and S. Bittanti (1990) [4] provided some simple rules relevant to the plant step response or impulse response. Then, based on D.W. Clarke and R. Scattolini (1991) [5], the constrained receding horizon predictive control optimizes cost function to stabilize the plant. Model Predictive Control concept has been extensively studied and widely accepted in industrial applications. The main reasons for such popularity of the predictive control strategies are the intuitiveness and the explicit constraint handling. The predictive controllers are used in many areas, where high-quality control is required [6].

There were several study performed to find an approach to damp the system frequency oscillation since the power stabilizer system (PSS) is designed to damp the local oscillation which is above 2 Hz [7] and [8]. Other studies introduced FACTS devices such as a thyristor controlled series capacitor (TCSC) to control the system frequency oscillation [9].

In this study, MPC will be used in the UPFC control scheme to prevent transmission system overloading and instability [10]. Model Predictive Controller can be used in Single Input Single Output (SISO), Muti Input Multi Output (MIMO), simple or complex processes. It was adopted for the industrial application and being used in a wide variety of industries and power applications. In this paper, the effectiveness and the capability of this type of controller in UPFC application will be discussed and compared with the convention PI controller.

## 2 UPFC Study

Gyupyi introduced the UPFC in 1991 [11]. It is composed of two voltage source converters linked by common d.c link as illustrated in Fig. 1.

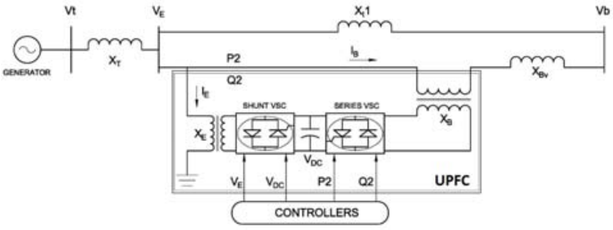

Figure 1: UPFC in SMIB.

Mathematical models for the steady state and dynamic model will be analyzed in order to inspect the performance of the UPFC in the system. The steady state model is concerned to determine the initial condition of the system to perform the load flow analysis. While, the dynamic model will be performed to ensure that the performance of the UPFC and its controllers during disturbance and any sudden load changes are acceptable and met the expectations. A. Nabavi-Niaki and M. R. Iravani [12] model is considered in this study as illustrated in Fig. 2.

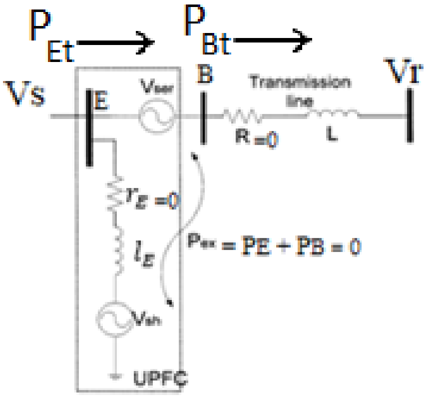

Figure 2: UPFC Decouple Model.

In this approach, the UPFC is replaced by equivalent bus representation in order to be transformed into a conventional power system, which can be analyzed and solved by using load flow technic. The main role of the UPFC in steady state is to perform the power flow analysis and the result of the initial condition will be used to determine the required converter control variables used for the PWM strategy such as modulation index and phase angle. UPFC can enhance the power flow, voltage, damping…etc by controlling the output control variables. The control outputs will The UPFC was considered as a losses system by negating the coupling transformer resistance. Moreover, the operation of the voltage source is not independent of each other and the total exchange UPFC power is equal zero.

$$\mathrm{P_E} + \mathrm{P_B} = 0 \tag{1}$$

So, the active power injection at the UPFC buses should be equal as the UPFC power exchange with the AC system is zero.

$$\mathrm{P_{Et}} + \mathrm{P_{Bt}} = 0 \tag{2}$$

The injected voltage to the converters assumed to be a pure sin wave signals by neglecting the higher order frequency components formed due to switching. The UPFC dynamic model can be represented by the d.c. link dynamic model, which compose of the series current, shunt current, modulation indexes and angles of both converters. The d.c. link dynamic model is determined as shown below.

$$\frac{d\upsilon_{dc}}{dt} = -\frac{3m_E}{4C_{dc}}\left|\cos\delta_E \quad \sin\delta_E\right| \begin{vmatrix} i_{Ed} \\ i_{Eq} \end{vmatrix} + \frac{3m_B}{4C_{dc}}\left|\cos\delta_B \quad \sin\delta_B\right| \begin{vmatrix} i_{Bd} \\ i_{Bq} \end{vmatrix} \tag{3}$$

$m_E$ and $m_E$ are the amplitude modulation ratios, while $\delta_E$ and $\delta_B$ are the phase angle of the voltage source converter control signal. $m_E$, $m_E$, $\delta_E$ and $\delta_B$ are selected to be connected to the control output signal to control $V_E$, $Q_2$ , $V_{dc}$ and $P_2$ respectively.

## 3 System Study

The UPFC is incorporated in a Single Machine to Infinite Bus (SMIB) system to test and analysis the entire system performance. Model number 1.0 of a synchronous generator with IEEE ST1A excitation system will be adopted as it is used in most of the dynamic studies of power system such as the studied performed by M.Abido [13], M. A. Abido et al.[14], and S A. Alqallaf [15].

$$i_{Ed} = \frac{x_{Bt}}{x_{d\Sigma}}E'_q - \frac{x_{d1}}{x_{d\Sigma}}\frac{m_E\upsilon_{dc}}{2}\sin\delta_E + \frac{x_{d2}}{x_{d\Sigma}}\frac{m_B\upsilon_{dc}}{2}\sin\delta_B + \frac{x_{d3}}{x_{d\Sigma}}V_b\cos\delta \tag{4}$$

$$i_{Eq} = \frac{x_{q1}}{x_{q\Sigma}}\frac{m_E\upsilon_{dc}}{2}\cos\delta_E - \frac{x_{q2}}{x_{q\Sigma}}\frac{m_B\upsilon_{dc}}{2}\cos\delta_B - \frac{x_{q3}}{x_{q\Sigma}}V_b\sin\delta \tag{5}$$

$$i_{Bd} = \frac{x_{Et}}{x_{d\Sigma}}E'_q + \frac{x_{d2}}{x_{d\Sigma}}\frac{m_E\upsilon_{dc}}{2}\sin\delta_E - \frac{x_{d4}}{x_{d\Sigma}}\frac{m_B\upsilon_{dc}}{2}\sin\delta_B - \frac{x_{d5}}{x_{d\Sigma}}V_b\cos\delta \tag{6}$$

$$i_{Bq} = \frac{x_{q2}}{x_{q\Sigma}}\frac{m_E\upsilon_{dc}}{2}\cos\delta_E - \frac{x_{q4}}{x_{q\Sigma}}\frac{m_B\upsilon_{dc}}{2}\cos\delta_B - \frac{x_{q5}}{x_{q\Sigma}}V_b\sin\delta \tag{7}$$

$$i_d = \frac{x_{c1}}{x_{d\Sigma}}E'_q - \frac{x_{Bt}}{x_{d\Sigma}}\frac{m_E\upsilon_{dc}}{2}\sin\delta_E + \frac{x_{Et}}{x_{d\Sigma}}\frac{m_B\upsilon_{dc}}{2}\sin\delta_B - \frac{x_{c2}}{x_{d\Sigma}}V_b\cos\delta \tag{8}$$

$$i_q = \frac{x_{Bt}}{x_{q\Sigma}}\frac{m_E\upsilon_{dc}}{2}\cos\delta_E - \frac{x_{Et}}{x_{q\Sigma}}\frac{m_B\upsilon_{dc}}{2}\cos\delta_B + \frac{x_{c2}}{x_{q\Sigma}}V_b\sin\delta \tag{9}$$

Where, $x_d$, $x_q$, $x_t$ and $x_d'$ are synchronous generator parameters. So for equation simplification:

$$x_{dt} = x_d' + xt \tag{10}$$

$$x_{qt} = x_q + x_t \tag{11}$$

$$x_{BB} = x_{B\upsilon} + x_B \tag{12}$$

$$x_{Bt} = x_{BB}x_{t1} \tag{13}$$

$$x_{Et} = x_E x_{t1} \tag{14}$$

$$x_{c1} = x_{BB}x_{t1} + x_E\left(x_{BB} + x_{t1}\right) \tag{15}$$

$$x_{d\Sigma} = x_{BB}x_{t1}\left(x_E + x_{dt}\right) + x_{dt}\,x_E\left(x_{BB} + x_{t1}\right) \tag{16}$$

$$x_{q\Sigma} = x_{BB}x_{t1}\left(x_E + x_{qt}\right) + x_{qt}\,x_E\left(x_{BB} + x_{t1}\right) \tag{17}$$

$$x_{d1} = x_{BB}x_{t1} + x_{dt}\left(x_{BB} + x_{t1}\right) \tag{18}$$

$$x_{d2} = x_{dt}x_{t1} \tag{19}$$

$$x_{d3} = x_{dt}\left(x_{BB} + x_{t1}\right) \tag{20}$$

$$x_{d4} = x_{t1}\left(x_E + x_{dt}\right) + x_{dt}x_E \tag{21}$$

$$x_{d5} = x_{t1}\left(x_E + x_{dt}\right) \tag{22}$$

$$x_{q1} = x_{BB}x_{t1} + x_{qt}\left(x_{BB} + x_{t1}\right) \tag{23}$$

$$x_{q2} = x_{qt}x_{t1} \tag{24}$$

$$x_{q3} = x_{qt}\left(x_{BB} + x_{t1}\right) \tag{25}$$

$$x_{q4} = x_{t1}\left(x_E + x_{qt}\right) \tag{26}$$

$$x_{q5} = x_{t1}\left(x_E + x_{qt}\right) \tag{27}$$

## 4 PI Control Design

PI controllers will be used to control the system variables in the SMIB, which contains a UPFC. In general, the PI controller coefficients can be tuned manually to obtain the desired output. In order to ensure that the system outputs are optimum, the PI coefficients should be chosen based on using the optimization algorithm. In this study, PI controller coefficients are selected from the study performed by S. A. Alqalaf [16], which he used an optimization algorithm to determine the PI coefficients. These coefficients are considered as a reference to compare and evaluate the output performance from the new proposed adaptive controllers which will be introduced in this paper. PI controllers are placed in four loops in order to regulate the real power in line 2, reactive power in line 2, D.C. voltage between the UPFC converters and finally the sending bus voltage $V_E$ as illustrated in Fig. 3. The PI controller outputs will be fed to UPFC which is connected to line 2 in SMIB and the outputs will be checked accordingly.

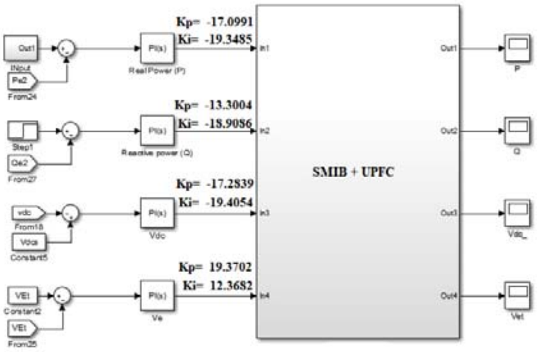

Figure 3: PI Controllers in SMIB with UPFC.

## 4.1 Dynamic Response Performance of PI Controller in Case of Sudden Step Change

The dynamic response waveform of the real power flow in line 2 with the UPFC installed in case of a sudden step change is illustrated in Fig. 4. It can be seen that, the reference signal which is equal to 0.5 p.u is reduced around 10% and the PI controller respond smoothly to this sudden change. In this case, the settling time is around 6 second and the overshoot voltage is acceptable.

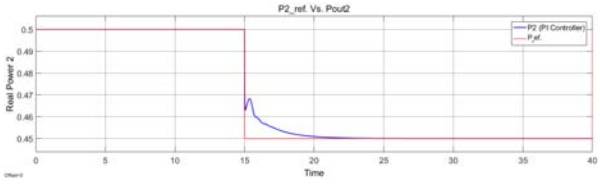

Figure 4: Real Power flow in line 2 by using PI Controllers in case of sudden step change (-10%).

Moreover, it can be noticed that the 10% reduction in power flow in line 2 is compensated in line number 1 in order to meet the load required which is equal to 1 p.u. as illustrated in Fig. 5. So, the power flow maneuver is achieved in this case satisfactorily. Also, it can be noticed that real power in line 2 has better performance than the real power flow in line 1 which has intentionally no controller for comparison purpose.

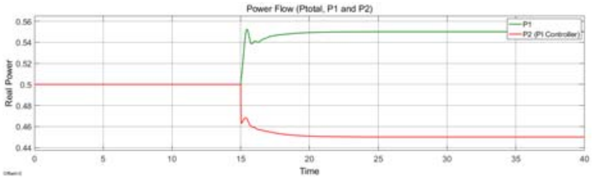

Figure 5: Real Power flow in line 1 and 2 by using PI Controllers in case of sudden step change (-10%).

## 4.2 Dynamic Response Performance of PI Controller in Case of Sudden Step Change and System Disturbance

To investigate the controller robustness, the reference signal for the real power in line 2 will be changed frequently by ±10%. Moreover, the load disturbance will be applied at 70 second and for one second duration as illustrated in Fig. 6. It is noticed that the PI Controller is responding to the frequent change in the reference signal but has a sluggish response and need 6 second for convergence. Small overshoot is observed equal to 3.5% due to the disturbance.

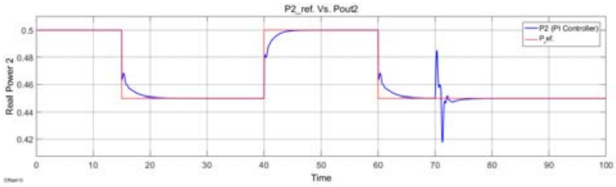

Figure 6: Real Power flow in line 2 by using PI Controllers in case of sudden step change (±10%) and sudden system disturbance.

In addition, both real powers in parallel lines are investigated as illustrated in Fig. 7. It has been noticed that any change in the power flow in line 2, it will be compensated in line 1 in order to deliver the required total power which is equal to 1 p.u. Furthermore, the PI controller in line 2 control the disturbance within 6 second with small overshoot, while line number 1 has overshoot around 17% as there is no controller installed in line number 1.

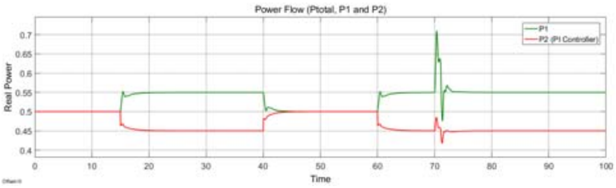

Figure 7: Real Power flow in line 1 and 2 by using PI Controllers in case of sudden step change (±10%) and sudden system disturbance.

# 5 Model Predictive Controller

## 5.1 The Concept of Model Predictive Controller

MPC refer to a type of computer control algorithms that utilize an explicit process model to predict the future response of the plant [17]. The concept behind MPC is that it takes the reference signals and the plant outputs and generate control outputs just like any other controller except it is using the inboard model of the plant to predict the behavior of the plant in future by any of the following method such as Kalman Predictor, BJ model, ARX, ARMAX or …etc. [18]. Future output predication is effected by the past state on future outputs, future inputs on future outputs and model mismatch.

The predicted behavior of the plant will be fed to an optimizer to adjust of the value of the control outputs to make sure that the predicted plant outputs track the reference signals. MPC is considered as a popular controller in industrial applications because at every time step the process executed in the control algorithm, there is optimization involved to give better control outputs. The MPC main components are:

Process model: to describe the process dynamics.

Objective function: can be referred as a cost function. Receding horizon method is considered to follow the predefined trajectory to predict future outputs taking into account the current and future constrains. The output calculated at each interval in horizon based on values at time t. then, it will be sent to the controller. An example of a non-linear cost function for optimization is given by Eduardo F. Camacho and Carlos Bordons [19]:

$$\mathrm{J} = \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{w_{xi}} (\mathrm{r_i} - \mathrm{x_i})^2 + \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{w_{ui}} \, \Delta \mathrm{u_i^2} \tag{28}$$

Without violating constraints (low/high limits) with
$\mathrm{x_i}$:$\mathrm{i^{th}}$ Controlled variable
$\mathrm{r_i}$:$\mathrm{i^{th}}$ Reference variable
$\mathrm{u_i}$:$\mathrm{i^{th}}$ Manipulated variable
$\mathrm{w_{xi}}$: Weighting coefficient reflecting the relative importance of $\mathrm{x_i}$
$\mathrm{w_{ui}}$: Weighting coefficient penalizing relative big change in $\mathrm{u_i}$

Controller: At each step, the optimization problem is formulated over the predication horizon. The control signals will be applied to the plant and in the next step will be recomputed based on the new system states [10].

## 5.2 MPC Model

The linear discrete model is logical basis for any predication and the common discrete state space model can be expressed as below:

$$x_{k+1} = Ax_k + Bu_k \tag{29}$$

$$y_k = Cx_k + d_k \tag{30}$$

Where ‘x’, ‘y’, ‘u’ and ‘d’ representing the State, Output, Control Input and Disturbance respectively. Discrete models are one step ahead predication model. So, at a simple ‘k’ the data can be determined for sample ‘k+1’.

$$y_{k+1} = Cx_{k+1} + d_{k+1} \tag{31}$$

by substituting $x_{k+1}$ from equation (29)

$$y_{k+1} = CAx_k + CBu_k + d_{k+1} \tag{32}$$

To simplify the equations, the disturbance could be assumed as follows:

$$d_{k+1} = d_k \tag{33}$$

The one-step ahead predication can be used recursively to find an n-step ahead predication as follows:

$$x_{k+1} = Ax_k + Bu_k \tag{34}$$

$$x_{k+2} = Ax_{k+1} + Bu_{k+1} = A\left[ Ax_k + Bu_k \right] + Bu_{k+1} \tag{35}$$

$$x_{k+3} = Ax_{k+2} + Bu_{k+2} = A\left[ \left[ Ax_k + Bu_k \right] + Bu_{k+1} \right] + Bu_{k+2} \tag{36}$$

$$x_{k+4} = Ax_{k+3} + Bu_{k+3} = A\left[ A\left[ \left[ Ax_k + Bu_k \right] + Bu_{k+1} \right] + Bu_{k+2} \right] + Bu_{k+3} \tag{37}$$

Rearranging the equation (35), (36) and (37) will be as follow:

$$x_{k+1} = Ax_k + Bu_k \tag{38}$$

$$x_{k+2} = A^2 x_k + ABu_k + Bu_{k+1} \tag{39}$$

$$x_{k+3} = A^3 x_k + A^2 Bu_k + ABu_{k+1} + Bu_{k+2} \tag{40}$$

$$x_{k+4} = A^4 x_k + A^3 Bu_k + A^2 Bu_{k+1} + ABu_{k+2} + ABu_k \tag{41}$$

So, the general expiration of the n-step ahead predications are shown below:

$$x_{k+n} = A^n x_k + A^{n-1} Bu_k + A^{n-2} Bu_{k+1} + \ldots + ABu_{k+n-2} + Bu_{k+n-1} \tag{42}$$

$$y_{k+n} = Cx_{k+n} + d_{k+n} \tag{43}$$

$$y_{k+n} = CA^n x_k + C\left(A^{n-1} Bu_k + A^{n-2} Bu_{k+1} + \ldots + ABu_{k+n-2} + Bu_{k+n-1}\right) + d_k \tag{44}$$

A double subscript will be used as a common notation to determine that the first term is identifying the sample of the predication i.e. how many step ahead. The second term represent the sample at which the predication was made like for example$x_{k+4/k}$ and $y_{k+6/k+2}$. So, equation (42) and (44) can be written as follows:

$$x_{k+n/k} = A^n x_k + A^{n-1} Bu_{k/k} + A^{n-2} Bu_{k+1/k} + \ldots + ABu_{k+n-2/k} + Bu_{k+n-1/k} \tag{45}$$

$$y_{k+n/k} = CA^n x_k + C\left(A^{n-1} Bu_{k/k} + A^{n-2} Bu_{k+1/k} + \ldots + Bu_{k+n-1/k}\right) + d_k \tag{46}$$

It is convenient to spilt the equation into two parts. The first part is based on the current and past measurement and the second part is for future input that remains to be decided. This is for the purpose of choosing the unknown inputs to ensure that the overall predication is satisfactory.

$$y_{k+n/k} = \underbrace{CA^n x_k + d_k}_{1^{st}\text{ Part}} + \underbrace{C\left(A^{n-1} Bu_{k/k} + A^{n-2} Bu_{k+1/k} + \ldots + Bu_{k+n-1/k}\right)}_{2^{nd}\text{ Part}} \tag{47}$$

Writing equation (45) in a vector form:

$$\begin{bmatrix} X_{k+1/k} \\ X_{k+2/k} \\ \cdot \\ \cdot \\ \cdot \\ X_{k+n/k} \end{bmatrix} = \begin{bmatrix} Ax_k \\ A^2 x_k \\ \cdot \\ \cdot \\ \cdot \\ A^n x_k \end{bmatrix} + \begin{bmatrix} Bu_{k/k} \\ ABu_{k/k} + Bu_{k+1/k} \\ \cdot \\ \cdot \\ \cdot \\ A^{n-1} Bu_{k/k} + \ldots + ABu_{k+n-2/k} + Bu_{k+n-1/k} \end{bmatrix} \tag{48}$$

$$\underbrace{\begin{bmatrix} X_{k+1/k} \\ X_{k+2/k} \\ \cdot \\ \cdot \\ \cdot \\ X_{k+n/k} \end{bmatrix}}_{\underset{\rightarrow}{x}_{k+1}} = \underbrace{\begin{bmatrix} A \\ A^2 \\ \cdot \\ \cdot \\ \cdot \\ A^n \end{bmatrix}}_{P_x} X_K + \underbrace{\begin{bmatrix} B & 0 & \ldots & 0 \\ AB & B & \ldots & 0 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ A^{n-1}B & A^{n-2}B & \ldots & B \end{bmatrix}}_{H_x} \underbrace{\begin{bmatrix} u_{k/k} \\ u_{k+1/k} \\ \cdot \\ \cdot \\ \cdot \\ u_{k+n-1/k} \end{bmatrix}}_{\underset{\rightarrow}{u}_k} \tag{49}$$

$$\underset{\rightarrow}{\mathrm{x}}_{\mathrm{k+1}} = \left[\mathrm{P_X x_k}\right] + \left[\mathrm{H_X}\,\underset{\rightarrow}{\mathrm{u}}_{\mathrm{k}}\right] \tag{50}$$

Also, writing equation (46) in a vector form

$$\underbrace{\begin{bmatrix} y_{k+1/k} \\ y_{k+2/k} \\ \cdot \\ \cdot \\ \cdot \\ y_{k+n/k} \end{bmatrix}}_{\underset{\rightarrow}{y}_{k+1}} = \underbrace{\begin{bmatrix} CA \\ CA^2 \\ \cdot \\ \cdot \\ \cdot \\ CA^n \end{bmatrix}}_{\mathrm{P}} y_k + \underbrace{\begin{bmatrix} CB & 0 & \ldots & 0 \\ CAB & CB & \ldots & 0 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ CA^{n-1}B & CA^{n-2}B & \underbrace{\ldots} & CB \end{bmatrix}}_{\mathrm{H}} \underbrace{\begin{bmatrix} u_{k/k} \\ u_{k+1/k} \\ \cdot \\ \cdot \\ \cdot \\ u_{k+n-1/k} \end{bmatrix}}_{\underset{\rightarrow}{u}_k} + \underbrace{\begin{bmatrix} d_k \\ d_k \\ \cdot \\ \cdot \\ \cdot \\ d_k \end{bmatrix}}_{\mathrm{Ld}} \tag{51}$$

$$\underset{\rightarrow}{y}_{k+1} = \left[Px_k + Ld_k\right] + H\,\underset{\rightarrow}{u}_k \tag{52}$$

So, it has been noticed from equation (50) and (52) that the second part of each equation contains of the control output ‘u’ which is only the unknown parameter and can be chosen in such way that the overall predication is desirable. This can be achieved by feeding the predicted behaviour of the plant to an optimizer to adjust of the value of the control outputs to make sure that the predicted plant outputs track the reference signals by minimizing the cost function in equation (28). At every time step the process executed in the control algorithm, there is optimization involved to give better control. Matlab toolbox for MPC will be used in order to train and design the controllers for UPFC control variables.

### 5.3 Dynamic Response Performance of MPC

The PI controller of the real power flow in line 2 ($P_2$) will be replace by MPC. The performance of the MPC controller will be examined in case of sudden step change and sudden system disturbance.

### 5.3.1 MPC Performance in Case of Sudden Step Change

The conventional PI controller used to control the real power in line 2 will be replaced by MPC as illustrated in Fig. 8. It has been noticed that the MPC controller is much faster than PI controller and stabilize the system in less than a second with negligible ripples (maximum 0.1%). This is because the optimization process of controller takes place in each time sample and indicates that the predicted system behavior is well accepted.

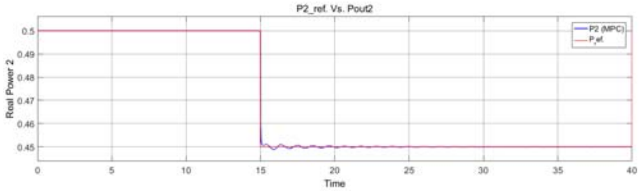

Figure 8: Real Power flow and 2 by using MPC in case of sudden step change (-10%).

The difference between the real power in line 1, which has no controller in place, and the real power in line 2 with MPC controller can be seen clearly in illustration Fig. 9. The real power in line 1 is oscillating and settled after 10 second, while line 2 responds to the step change effectively. The reference power in 2 decreased and the balance is transferred to line 1 as expected.

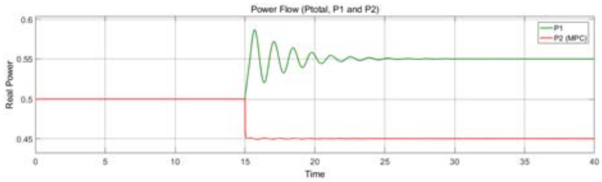

Figure 9: Real Power flow and 1 and 2 by using MPC in case of sudden step change (-10%).

### 5.3.2 MPC Performance in Case of Sudden Step Change and Sudden System Disturbance

Several step changes ± 10% in the reference signal of the real power in line 2 are introduced to the system to examine the MPC controller. Also 10% sudden increase in load demand at second 70 and removed after a second i.e. at second 71 as illustrated in Fig. 10. The MPC controller proves its ability to stabilize the system and damp the oscillation better and faster than the conventional PI controller. The maximum overshoot is around 0.5% which much less than the PI controller output.

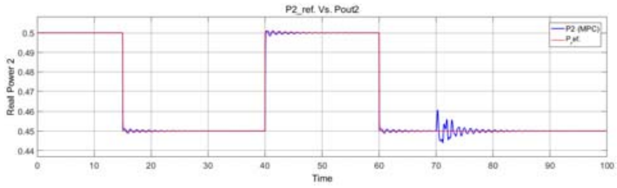

Figure 10: Real Power flow in line 2 by using MPC in case of sudden step change (±10%) and sudden system disturbance.

The difference between the real power in line 1 which has no controller in place and the real power in line 2 with MPC controller is illustrated in Fig. 11. The real power in line 1 is oscillating and settled after 12 second, while line 2 respond to the step change effectively within less than a second.

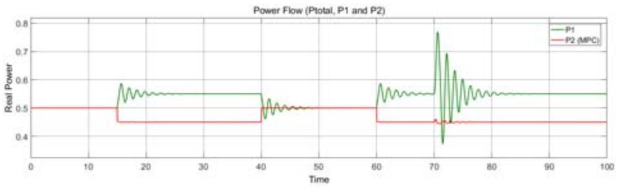

Figure 11: Real Power flow in line 1 and 2 by using MPC in case of sudden step change (±10%) and sudden system disturbance.

### 5.3.3 Comparison between PI controller and MPC

Figure 12 shows the dynamic performance of PI controller and Model Predictive Controller in the system. Although, both types of controller are efficient to stabilize the system, but the time response for each one of them is entirely different. The fastest response is the MPC. The PI controller has a sluggish and smooth response compared to MPC.

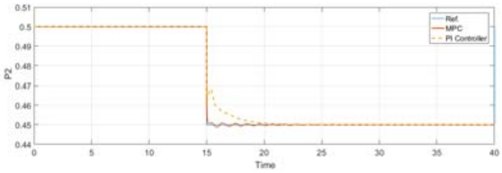

Figure12: MPC and PI Controller performance in case of a sudden step change.

The system has also undergone to several change in the reference real power signal which equal to ± 10%. Moreover, 10% of a sudden increase in the load at time 70 second was added to the system. Then, after one more second 10% of the load is disconnected again to make stress in the system to examine the functionality of the proposed controller. It has been clearly shown in Fig. 13 that both types of controllers are responding to the system change satisfactorily. MPC controller has the best performance and fast response among PI controller, which mean that the predicted model and the control optimization is effective.

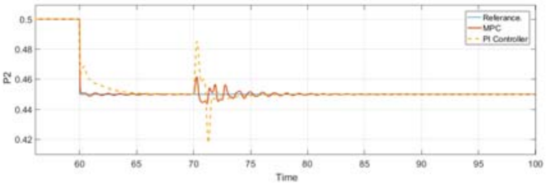

Figure 13: MPC and PI Controller performance in case of a sudden step change and load disturbance.

The performance of all controllers have been examined, verified and compared to have solid and accurate decision. The controllability, convergence, steady-state, damping oscillation, overshoot and transient response are the selected criteria to evaluate the controller's capabilities. The given rating score are varying between 1 and 5 as shown below in table (5.1), where 1 is considered as poor and 5 represent that the controller is exceptional.

## 6 Conclusion

The capability of controlling the system parameters in the transmission lines which consist of UPFC was verified and found that the steady state and dynamic behavior of the power system was enhanced in presences of the UPFC and the adaptive controllers. The robustness, controllability and the effectiveness of the proposed adaptive controllers has been proven. So, the proposed controller can perform the same functionality of the PI conventional controllers and even faster than PI controllers which have sluggish response and cannot accommodate to some extent the new change in the system. Model Predictive Control has better response than PI controllers during the transient period.

*Refrences:*

[1] Shahriar, M. S., Ahmed, M. A., Rahman, M. I., & Khan, A. I. (2013). Comparison of MPC and conventional control methods for the stability enhancement of UPFC connected SMIB system. *2nd International Conference on Advances in Electrical Engineering (ICAEE),* 223-228. doi:10.1109 /ICAE E.2013.6750337.

[2] Garcia, C. E., Prett, D. M., & Morari, M. (1989). Model predictive control: Theory and practice- A survey. *Automatica, 25*, 3rd ser., 335-348. Retrieved from https://doi.org/10.1016/0005-1098(89)90002-2.

[3] De Keyser, R., Van de Velde, P., & Dumortier, F. (1988). A comparative study of self-adaptive long-range predictive control methods. *Automatica, 24*(2), 149-163.

[4] Scattolini, R., & Bittanti, S. (1990). On the Choice of the Horizon in Long-Range Predictive Control—Some Simple Criteria. *Automatica, 26*(5), 915- 917. doi:10.1016/0005-1098(90)90009-7.

[5] Clarke, D. W., & Scattolini, R. (1991). Constrained receding-horizon predictive control. *IEE Proceedings D (Control Theory and Applications), 138*(4), 347-354. doi:10.1049/ip-d.1991.0047.

[6] Badgwell, T. A. (1997). A Robust model prective control algorithm for stable nonlinear plants. *IFAC Proceedings Volumes, 30*(9), 535-539. Retrieved from https://doi.org/10.1016/S1474-6670(17)43204-6.

[7] Jain, A., Chakrabortty, A., & Blylk, E. (2017). An Online Structurally Constrained LQR Design for Damping Oscillations in Power System Networks. *American Control Conference,* 2093-2098.

[8] Jain, A., Chakrabortty, A., & Biyik, E. (2018). Distributed wide-area control of power system oscillations under communication and actuation constraints. *Control Engineering Practice, 74,* 132-143. Retrieved from https://doi.org/10.1016/j.conengprac.2018.03.003.

[9] Aranya Chakrabortty, A. (2012). Wide-Area Damping Control of PowerSystems Using Dynamic Clustering and TCSC-Based Redesigns. *IEEE TRANSACTIONS ON SMART GRID, 3*(3), 1503-1514.

[10] Sun, J., Zheng, H., DeMarco, C. L., & Chai, Y. (2016). Energy function based model predictive control with UPFCs for relieving power system dynamic current violation. *IEEE Transactions on Smart Grid, 7*, 6th ser., 2933-2942. doi:10.1109/TSG.2016.2582878

[11] Gyugyi, L. (1992). Unified power-flow control concept for flexible AC transmission systems. IEE Proceedings C (Generation, Transmission and *Distribution), 139*, 4th ser., 323-331. doi:10.1049/ip-c.1992.0048

[12] Nabavi-Niaki, A., & Iravani, M. R. (1996). Steady-state and dynamic models of unified power flow controller (UPFC) for power system studies. IEEE IPES Winter Meeting, 447-454.

[13] M. A. (2005). Analysis and assessment of statcom-based damping stabilizers for power system stability enhancement. *Electric Power* Systems Research, 73, 2nd ser., 177-185.

[14] Abido, M., Al-Awami, A., & Abdel-Magid, Y. (2006). Analysis and design of upfc damping stabilizers for power system stability enhancement. *IEEE* International Symposium on Industrial Electronics, 3, 2040-2045.

[15] Alqallaf, S.A (2005). Smart controller design for unified power flow controller using evolutionary optimaization algorithms. Kingdom of Bahrain: UOB.

[16] Qin, S., & Badgwell, T. (2002). A survey of industrial model predictive control technology. *Control Engineering Practice, 11*, 733-764.

[17] Patwardhan, S. C. (n.d.). Linear quadratic optimal control and model predictive control. Retrieved 2014, from http://nptel.ac.in/courses/103101003/downloads/lecturenotes/APC_Part_7_LQG_and_MPC.pdf.

[18] Camacho, E. F., & Bordons, C. A. (2007). *Model predictive control* (2nd ed.). London, UK: Springer-Verlag. doi:10.1007/978-0-85729-398-5

[19] Gorinevsky. (2005). Lecture 14 model predictive control. Retrieved from https://web.stanford.edu/class/archive/ee/ee392m/ee392m.1056/Lecture14_MPC.pdf.