Design of Model Predictive Controller (MPC) for Load Frequency Control (LFC) in an Interconnected Power System

K.Vimala Kumar, K.Bindiya

Abstract— **In the power system, any sudden load changes leads to the deviation in tie-line power and the frequency. So load frequency control is an issue in power system operation and control for supplying sufficient and reliable electric power with good quality. The main goal of the load frequency control of a power system is to maintain the frequency of each area and tie-line power flow with in specified tolerance by adjusting the MW outputs of LFC generators so as to accommodate fluctuating load demands. In this paper, a Model Predictive Control (MPC) algorithm is used so that the effect of the uncertainty due to governor and turbine parameters variation and load disturbance is reduced. In power system load changes are immeasurable in order to measure these changes Fast Sampling Method (FOS), is used as it reduces the estimation error to zero after just one sampling period and Feed- forward control method is used for rejecting load disturbance effect in each power system area by MPC. In this paper, parameters ensure stability, accuracy and robustness of load-frequency control system. Obtained parameters are tested on simulations, which are conducted on a 3-Area deregulated power system model. The results are compared with a recently proposed robust LMI based PI control strategy. This comparison confirms that the proposed method has better performance than the LMI based PI controller in the presence of disturbances and uncertainties so that the frequency deviation and power flow changes between areas are effectively damped to zero with small oscillations in a short time.**

Index Terms— **Deregulated Power system, Load Frequency Control, Model predictive control, Fast output sampling method, Load disturbance, Parameter uncertainty.**

I. Introduction

Power system is a complex, nonlinear system consisting of several interconnected subsystems or control areas (CA). Frequency of power system and active power flow between CAs deviate in time caused by differences between generation and consumption in a CA. In each CA, load-frequency control (LFC) ensures maintenance of the area's frequency at desired constant value and also ensures scheduled active power interchange with the neighbour CAs. A numerical measure of CA's deviation from the regular behaviour is area control error (ACE) signal, which is a combination of frequency deviation in the CA and active power flow variations in the tie lines with the neighbour areas. The goal of LFC is to ensure ACE signal is to be zero. In many industries, PI type controllers are used for LFC. Systems with PI load-frequency controllers have long settling time and relatively large overshoot in frequency's transient response. However, robust control algorithm and good transient response are needed for LFC. Recently, Model predictive control (MPC) has been also introduced as a new method for load frequency control design.

MPC is a model based control strategy where an optimization procedure is performed in every sampling interval over a prediction horizon, giving an optimal control action. The optimization procedure is chosen in such a way to satisfy the controlled system dynamics and constraints, penalize system output deviation from the desired trajectory, and minimize control effort. It has many advantages such as very fast response, robustness and stability against nonlinearities constraints and uncertainties. Considering desirable properties of MPC, these controllers are applied in a wide range of different industries, particularly in the process industries [11].Moreover a possibility to comprise economic objectives into the optimization criterion makes the MPC a good candidate for power system control. It presented a new model predictive load frequency control including economy logic for LFC cost reduction. In [14], a new state contractive constraint-based predictive control (SCC-MPC) is proposed for LFC synthesis of a two area power system. In [15], practical MPC (FC-MPC) method is used in distributed LFC instead of centralized MPC and it has been applied to a four control area as a large scale power system. This paper only has investigated the effect of very large load changes on the frequency and power flow between areas. A decentralized MPC is proposed recently for load frequency control problem in[16], where the performance of the controller against parameter uncertainties and load changes on two and three control area power system is evaluated. In this paper, the variation of governor and turbine parameters are considered as uncertainties while in practice these parameters may not change for a long time. Actually the main source of uncertainty is related to variations of power system parameters rather than generating unit parameters. Also, the range of load change that used in [16] is not very large; nevertheless, the results do not show better behaviour in transient response in comparison with conventional PI.

The present paper deals with a decentralized model predictive scheme to LFC synthesis of multi area power systems by considering large load changes and parameter uncertainties of power system. In the proposed controller, load changes and interconnection between control areas are defined as measured and unmeasured disturbances, respectively. Practically the load changes are immeasurable in

Manuscript received October 30, 2013.
K.Vimala Kumar, Assistant Professor, J.N.T.U.A College Of Engineering Pulivendula, A.P, INDIA-516390
K.Bindiya, G student, J.N.T.U.A College Of Engineering Pulivendula, A.P, INDIA-516390

a power system, Fast Output Sampling (FOS) method is used to estimate load disturbance as an input to MPC controller and feed-forward controller is to reject the effect of load disturbance. To evaluate the effectiveness of the proposed controller, a three area interconnected power system is considered as a test case. Validation of the MPC controller has been done also by its comparison with the addressed robust PI control design in [3]. The simulation result shows that the proposed controllers ensures the robust performance in the presence of uncertainties due to power system parameters variation and loads.

II. TRADITIONAL MODEL

Deregulated power system consists of GENCO's, DISCO's and TRANSCO's and independent system operator (ISO). In general large power systems consists many number of interconnected area with the generating companies (GENCOs) which are composed of three major parts: governor, turbine and generator. Tie-line power deviation is proportional to the integral of the frequency difference between the two areas connected with the tie-line. The deviations from desired values are defined as Area Control Error (ACE). The ACE for each control area is expressed as a summation of tie-line power change (ΔP_{tie}) and frequency deviation (Δf) multiplied by a bias factor B.

$$ACE = \Delta P_{tie} + B\Delta f \qquad (1)$$

Changes in load produces changes in the electrical torque of the generator, results in a mismatch between the mechanical and electrical torque, resulting in speed variations. The governor will sense the change in speed, and adjust the valve position to increase/decrease flow toward turbine in order to balance the torque mismatch (primary loop). In the steady state, the generation should be matched with the load, driving the tie-line power and frequency deviations to zero. The primary control loop restores the balance between generation and demand in a small limit around the nominal frequency, therefore a supplemental or secondary control unit is needed. Usually a large scale power system has many control areas with several Gencos putting together. Fig. 1 shows the block diagram of control area-*i*, which includes *n* Gencos, from an N-control area power system

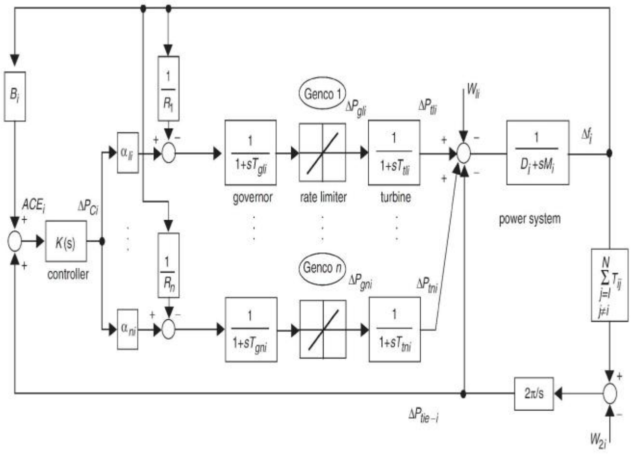


Fig. 1: The proposed MPC of the two-area load frequency control.

Generally a large scale power system has many control areas with several Gencos putting together. Fig. 1 shows the block diagram of control area-*i*, which includes *n* Gencos, from an N-control area power system. . By ignoring the nonlinearities in the model, a linearized mathematical model of area *i*, with n generating units can be written:

Governor:

$$\Delta \dot{P}_{gki} = -\frac{1}{T_{gki}}\Delta P_{gki} + \frac{1}{T_{gki}}\left(\frac{1}{R_k}\Delta f_i + \alpha_{ki}\Delta P_{ci}\right)$$

Turbine: $$\Delta \dot{P}_{tki} = -\frac{1}{T_{tki}}\Delta P_{tki} + \frac{1}{T_{tki}}\Delta P_{gki}; k = 1,\ldots n \qquad (2)$$

Generator:

$$\Delta \dot{f}_i = -\frac{D_i}{M_i}\Delta f_i + \frac{1}{M_i}\left(\sum_{l=1}^{n}\Delta P_{tli} - \Delta P_{tie_i} - W_{1i}\right)$$

The tie-line power deviation between area *i* and area *j* is defined as:

$$\Delta P_{ij} = T_{ij}(\Delta\delta_i - \Delta\delta_j) \qquad (3)$$

where $\Delta\delta_i$ and $\Delta\delta_j$ are the phase angle deviations in areas i and j. With $\Delta\dot{\delta}_i = 2\pi f_i$, a state equation for ΔPtiei for area i can be written:

$$\Delta P_{tie\_i} = \sum_{\substack{j=1 \\ i\neq j}}^{N}\Delta \dot{P}_{ij} = 2\Pi\sum_{\substack{j=1 \\ i\neq j}}^{N} T_{ij}(\Delta f_i - \Delta f_j) \quad (4)$$

Dynamic model of the system as described with equations (2) and (4) in a state space form is given with:

$$\dot{x}_i = A_i x_i + B_{ui}u_i + B_{wi}W_i$$
$$y_i = C_i x_i \qquad (5)$$

Where

$$x_i = [\Delta f_i \;\; \Delta P_{tie_i} \;\; \Delta P_{g1i} \;\; \Delta P_{t1i} \;\ldots\; \Delta P_{gni} \;\; \Delta P_{tni}]$$

$$u_i = \Delta P_{ci}; W_i = [W_{2i} W_{1i}]^T; W_{2i} = 2\pi\sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij}\Delta f_j$$

$$W_{1i} = \Delta P_{ci}; W_{2i} = 2\pi\sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij}\Delta f_j$$

$$A_i = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}; B_{ui} = \begin{bmatrix} 0_{2\times 1} \\ B_{u2} \end{bmatrix}; B_{wi} = \begin{bmatrix} B_{w1} \\ 0_{2n\times 2} \end{bmatrix}$$

$$A_{11} = \begin{bmatrix} -\frac{D_i}{M_i} & -\frac{1}{M_i} \\ 2\pi\sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij} & 0 \end{bmatrix}; A_{12} = \left[\begin{bmatrix} \frac{1}{M_i} & 0 \\ 0 & 0 \end{bmatrix} \ldots\ldots \begin{bmatrix} \frac{1}{M_i} & 0 \\ 0 & 0 \end{bmatrix}\right]$$

$$A_{21} = \begin{bmatrix} \begin{bmatrix} -\frac{1}{T_{g1i}R_1} & 0 \\ 0 & 0 \end{bmatrix} \\ \vdots \\ \begin{bmatrix} -\frac{1}{T_{gni}R_i} & 0 \\ 0 & 0 \end{bmatrix} \end{bmatrix};$$

$$A_{22} = \begin{bmatrix} \begin{bmatrix} -\frac{1}{T_{g1i}} & 0 \\ \frac{1}{T_{t1i}} & -\frac{1}{T_{t1i}} \end{bmatrix} & \cdots & 0_{2n-2\times 2n-2} \\ \vdots & \ddots & \vdots \\ 0_{2n-2\times 2n-2} & \cdots & \begin{bmatrix} -\frac{1}{T_{gni}} & 0 \\ \frac{1}{T_{tni}} & -\frac{1}{T_{tni}} \end{bmatrix} \end{bmatrix}$$

$$A_{u2} = \begin{bmatrix} \begin{bmatrix} \frac{\alpha_1}{T_{g1i}} \\ 0 \end{bmatrix} \\ \vdots \\ \begin{bmatrix} \frac{\alpha_n}{T_{gni}} \\ 0 \end{bmatrix} \end{bmatrix} ;\ B_{w1i} = \begin{bmatrix} 0 & -\frac{1}{M_i} \\ -1 & 0 \end{bmatrix} ;\ C = [\beta_i \quad 1 \quad 0_{1\times 2n}]$$

In the state-space model representation (5), x_i *is* the area state vector, y_i is the area output vector, u_i is the area input (ΔP_{ci}), and W_i is the area disturbance that includes changes in local load w_{1i} , as well as the area interface w_{2i}. The other parameters are described as follows.

f area frequency
ACE area control area
P_g governor valve position
P_c governor load set point
P_t turbine power
P_{tie} net-tie line power flow
P_d power demand(area load disturbance)
M equivalent inertia constant
D area load damping coefficient
T_g governor time constant
T_i turbine time constant
T_{ij} tie-line synchronizing between areas i and j
B frequency bias
α participation factor
R drooping characteristic
Δ deviation from nominal values
N number of control areas

III. MODEL PREDICTIVECONTROLLER

Model Predictive Control (MPC) has become an effective and accepted control strategy in chemical, oil, automotive, structural and many other industries. It is an open loop control scheme based on a system model, where in a sampling interval the future system behavior is predicted over a finite prediction horizon, and a sequence of future control signals is calculated by minimization of a performance index. Only the first control signal from the sequence is used as the system input, while the rest of the signal sequence is not considered. The whole procedure is repeated in the next sampling interval with the prediction horizon moved one sampling interval forward. The system output is taken into consideration in the optimization procedure through the error between the actual measured output in the current sampling interval and the prediction of the output made in the previous sample. Since the future system behavior is calculated over a shifted prediction horizon, model predictive control is also called receding or moving horizon control.

A general MPC scheme is shown in Fig. 2. The MPC controller consists of two units i.e., prediction and controller unit .The prediction unit includes system and disturbance model which estimates future behaviour of system based on its current output, measured disturbance, unmeasured disturbance and control signal over a finite prediction horizon. The predicted output is fed to control unit as known parameters to minimize an objective function in presence of system constraints in an optimization problem.

A general scheme MPC is presented in Figure 2. First, an appropriate system model and optimization objective is specified. The model will be used to determine the future system responses ˆy(k + 1), hence it needs to include the dynamics of the system. Then, a desired reference trajectory $y_r(k + 1)$ and constraints on output and control variables are defined. Prediction of the future system behavior is then made over a prediction horizon, based on the information about past system behavior and the sequence of future control signals that are required to satisfy the optimization objective. The error of the previous step output prediction is calculated as $e(k) = y_m(k) - \hat{y}(k)$, where $y_m(k)$ is the actual measured output and ˆy(k) is the prediction of the output made in the previous sample. This error is taken into account in the optimization procedure. A part of the prediction error accounts for the system model uncertainties, and the other part accounts for the effects of unmeasured disturbance on the system output. The first of the calculated control signals is implemented as the input to the system till the new measurements are available. In the next sampling interval the actual system output ym(k+1) is obtained and the whole procedure is repeated.

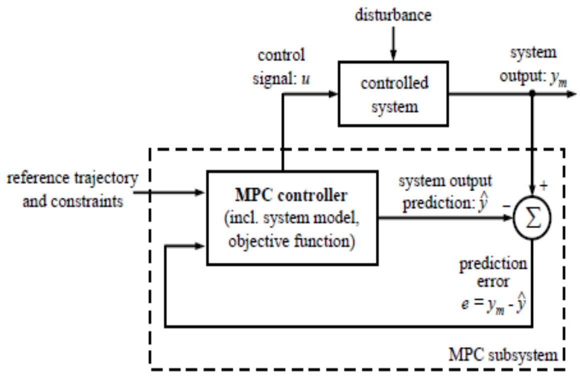


Fig.2:A general scheme of MPC Controller

When the effect of load disturbances are measured or estimated, then MPC controller provide an feed forward compensation for attenuating the impact of these disturbances on the output.In feed forward control corrective action is taken as soon as disturbances occurs. This control does not affect the stability of the processes. A more precisely disturbance-output model identified, a more effectively measured disturbance would be rejected. Since there is always difference between exact and identified model, feed-forward control has to be used in combination with feed-back control; the feed-forward control removes most of the measured disturbance effect, and the feedback control removes the rest as well as dealing with unmeasured disturbances. Feed-forward is easily incorporated into predictive control. All that has to be done is to include the effects of the measured disturbances in the predictions of future outputs. The optimizer will then take these into account when computing the control signal. More details of this strategy could be found in [18].

IV. MODELPREDICTIVELOAD FREQUENCY CONTROL

In this section, the decentralized model predictive control scheme is adopted on the LFC problem in a general N-control area power system described in section 2. For this reason, an MPC controller is applied to each control area to drive the tie-line power and frequency deviations to zero in the presence of load changes and parameter uncertainties, while the interconnection between control areas is considered.

The proposed MPC controller uses a feed forward control strategy to reject the effect of load disturbances. Fig. 3 illustrates the proposed strategy for area *i*. As it can be seen in this structure, an MPC controller has been used to generate the control signal based on ACE_i, Δf_i and $\Delta\hat{P}_{di}$ as its inputs. Since, load changes in power systems are not measurable practically; an estimator unit is used to obtain ΔACE_i.

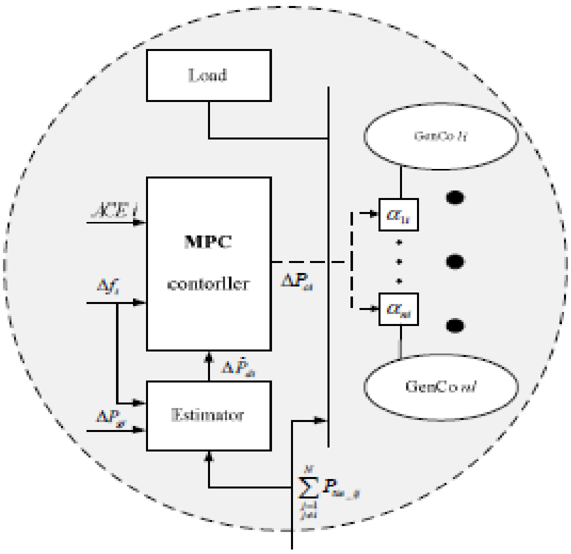


Fig.3.Proposed control strategy for area i

V. SIMULATIONS RESULTS

To design of MPC controller, the sampling interval of 0.1 second, the control horizon of 10 samples (m = 1) and a prediction horizon of 200 samples (p = 20) are selected as appropriate length to achieve good control performance. Moreover, Weights on system's input, output and state variables are chosen attain best quantities .To evaluate the performance of the decentralized MPC controller, it is compared to PI controller [4] in two different scenarios. In the first case, the robustness of the controllers in the presence of harsh sudden load changes such as generating unit loss is evaluated. The effectiveness of MPC controller in the face of power system uncertainty due to the inertia constant (*M*) and loa damping coefficient (*D*) perturbation is shown in scenario 2.

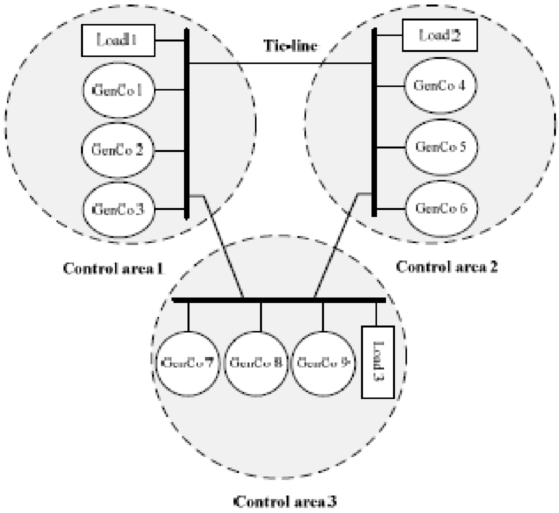


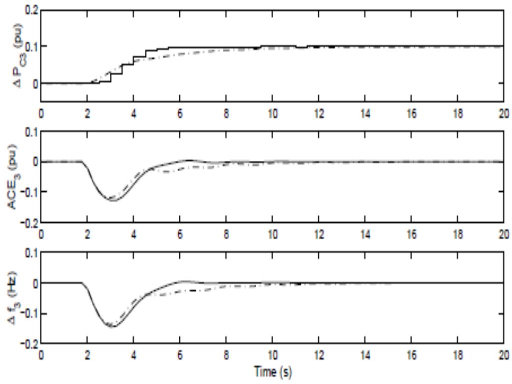
Fig.4.Three area power system

Scenario 1: for the first scenario, a large step load change in demand is added to each area at time *t=2sec* with the following quantities: ΔP_{d1}=150MW, ΔP_{d2}=120MW, and ΔP_{d3}=200MW.It can be seen that in spite of harsh conditions, the MPC controller still has better performance than PI controller so that the ACE and frequency deviation are effectively damped to zero with small oscillations in a very short time. The purpose of this scenario is to test robustness of the proposed controller against sudden changes in demand. For this case, generating rate constraint (GRC) was not imposed on the system. As for the previous scenario, closed-loop responses of the governor set point (ΔPC), area control error (ACE) and frequency deviation (Δf) of control areas 1, 2 and 3 are identified as important, It can be observed that the control inputs ΔPC in all control areas are efficiently increased to match the demand, without overshoots and oscillations.

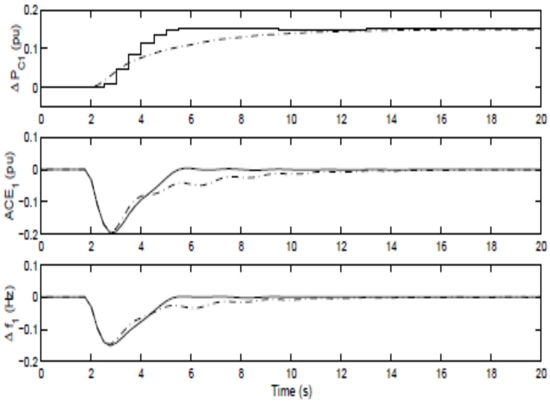
The ACE and frequency deviation Δf are driven to zero shortly after the disturbance occurred, with very small oscillations. Under this type of scenario, the MPC controller performs somewhat better than the GALMI tuned PI controllers.

During one sampling periods (*t*), several measurements of frequency deviation Δf (kt) and tie-line power deviation ΔP_{tie} (kt) signals are gathered. Besides those subsamples, which are inputs to the MPC controller, subsamples of generated power deviation ΔP_g (kt) are also gathered as inputs to the estimator. The formulation of the proposed disturbance estimation method is completely discussed in [13].

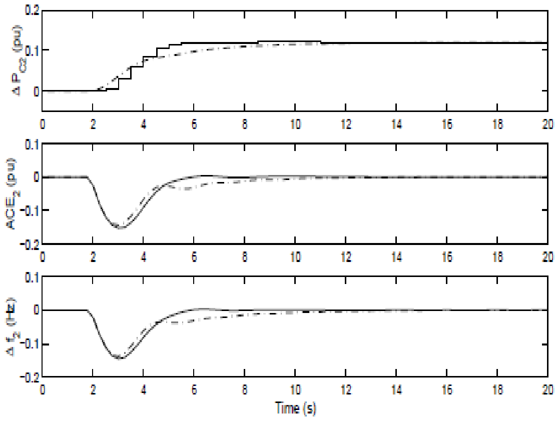
The performance of the MPC controllers is slightly better that of the PI controllers, with faster recovery time and less oscillations. This scenario tests robustness of the proposed control design against severe conditions, giving enough time to the operator to make appropriate actions, such is rescheduling of the existing generation or introducing the reserves, and to update the system model within the control algorithm with more accurate one.



(a)Area1



(b)Area2



(c)Area3

VI. Conclusion

The proposed controller is implemented in a completely decentralized fashion, using Area Control Error signal as the only input. A model of a three-area nine-generator system is chosen to present the effectiveness of the Model Predictive LFC controller. The control actions are calculated based on a step response model of the system, with the objective to minimize the effects of uncontrolled changes in area's native load and area's interconnections with the neighboring areas. These effects are treated in control algorithm as unmeasured disturbances and taken into calculations through the error between the measured system output and its prediction. Simulation results for several scenarios, including normal system operation, large load disturbance in all areas, and loss of a generating unit, have shown a good performance of the proposed MPLFC controller. For all considered cases, the control actions are taken effectively and in timely manner. Furthermore, a comparison with performance of a GALMI tuned PI controllers showed advantages of the proposed control design, especially for the case when significant rate limiter nonlinearities were imposed on the system.

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K.Vimala Kumar received the Master of Technology degree in Electrical & Electronics Engineering from Jawaharlal Nehru Technological University Hyderabad, India 2008. He is a research student of Jawaharlal Nehru Technological University, Ananthapur, India. Currently .He is working as Assistant Professor in the department of Electrical and Electronics Engineering, J.N.T.U.A College of Engineering, Pulivendula-516390, Andhra Pradesh, India. His interested areas are power system deregulation, power system operation and control, power system design and dynamic load modelling.

K.Bindiya is pursuing M.Tech in Electrical Power Engineering from JNTUA College of Engineering Pulivendula-516390, Andhra Pradesh, India. She is presently working on her project under the guidance of Asst.Professor K.Vimala Kumar