Model of induction motor changes to power system disturbances

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ABSTRACT

The power system consists of composite loads with different characteristics. To aggregate these and represent in equivalent models, is important to develop appropriate load modeling. A composite load consists of static and dynamic load. The main componment of dynamic load, is the induction motor. So it is important to model dynamic nature of an induction motors with shaft loads accurately. The main objective of this paper to develop an induction motor with different types of shaft loads to model of real (ΔP) and reactive (ΔQ) power changes to power system Voltage (ΔV), frequency (Δf) random changes.
The new developments are to consider cases where the system affects the load as well as having the load affect the system. A new tool to examine this case is presented.
It is really important to verify objective truth by experimental analysis. So, the second objective of the paper is to analyze the measured data from a QLD substation to confirm the model.

1. INTRODUCTION

For power system analysis, load modelling is very important [1-3].Load model is mathematical representation of real and reactive power changes to power system voltage and angle (frequency) changes [4].Traditionally there are two types of load modelling, static and dynamic [5]. There is a substantial component of load dynamics in the frequency range of system stability, so it is necessary to consider dynamic behaviour of loads [6]. Motors consume 60-70% of the energy from the power system, therefore, the dynamic characteristic of motors are critical for dynamic load modelling [5].

Many research papers have been published about load modelling [7-10]. The majority of those papers considered a composite load model consisting of static and dynamic load. As a dynamic load they considered as an induction motor .But these paper didn't consider induction motor with different kinds of shaft loads with variable power system parameters. Induction motors are major loads in any power system so it is important to model induction motor with dynamic shaft loads accurately.

Many research papers have been published on load modelling of induction motors [11-12]. In [11] they presented an off line method and an on-line method. For the off line method considered the no load and lock rotor test .For on line test, the motor is already connected to the industrial load. The paper used a 5^{th} order model. In paper [12], the motor examined is loaded with position-dependant loads. The authors used time varying frequency generalized averaging method to determine the model of 2 phase induction motor,.

In this paper, rotor speed dependant loads have been used. To identify the model, cross- correlation identification method has been used with simple 1^{st} order induction motor (which ignores the electrical transient). MATLAB is being used to simulate the motor model and apply nonparametric identification process of "cross-correlation".

Each of the examined papers on load modelling [7-10], consider only the variation of the power system generation parameters. But the general case for the load model is that power system affects the load and load will affect the power system measurement. So, new technique develops here for load model to consider the load affects to power system. The last section includes real data to explain the theory.

2. THEORY FOR CROSS-CORRELATION IDENTIFICATION [13]

Estimating an impulse response from input-output measurements is a component of system identification [14].

One path is to compute the impulse response of a filter from the cross-correlation of its input and output signals.

The system of cross-correlation based identification is presented in figure.1.

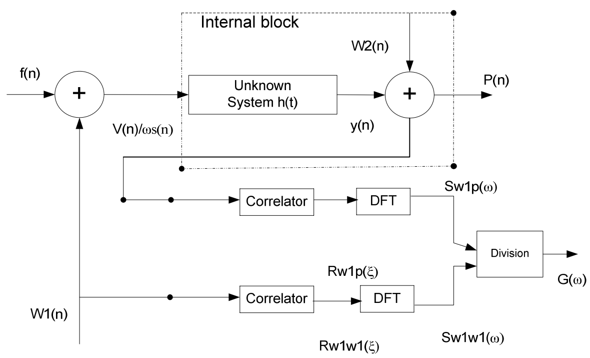

Figure 1.Cross-Correlation based identification

The measured system variable could be voltage or frequency. Due to other loads the variations in the measurement may not be predictable from past measurements or load effects. This is represented as a white noise input w1. Similarly there is a component of load variation which represents the unpredictable changes in load power by customers turning switches ON and OFF. This white noise component is represented by w2.

w1 added to the normal steady-state operation signal f(n).(f(n) is either steady-state voltage or steady-state supply frequency) and the sum v(n)/ ω_s(n) =w_1(n)+f(n) forms the input to the identified system(induction motor with different kinds of shaft load).consider induction motor an ideal linear system which doesn't generate any internal noise ,to the output y(n) of which a noise signal w_2(n) is added. Assuming the noise generally independent of both w_1 (n) and y (n), models the noise which is internally generated by any real system.

$\{w_1(n)\}$ is connected to the first input of the correlator, the other input of which is supplied by the additive signal, p (n) =y (n) +w_2 (n) as measured at the output of the system and input of the correlator thus produces an estimate of the correlation function $R_{w_1 p}(\tau)$ **.**

The internal linear block is described by the input –output convolution relationship

$$y(n)=\int_0^{\alpha} h(s)v(n-s)ds \qquad (1)$$

Where, h(s) is the impulse response of the induction motor with different kinds of shaft load.

If realized in discrete time domain, the cross-correlation function depends on the delay ξ as

$R_{w_1 p}$ =E {w_1 (n) p (n+ ξ)}

After substitution of the value of p,

$R_{w_1 p}$ =E {w_1(n) (y(n+ ξ) +w_2(n)(n+ ξ)}

$$R_{w_1 p}(\xi)=E\{w_1(n)\int_0^{\alpha} h(s)v(n+\xi-s)ds+w_2(n+\xi))\}$$

Expanding the product and using the linearity of the mean-value operator which enables us to interchange it with the integrator operator, obtain

$$R_{w_1 p}(\xi)=E\{w_1(n)w_2(n+\xi)\}+\int_0^{\infty} h(s)E\{w_1(n)(w_1(n+\xi-s)+f(n)(n+\xi-s))\}ds$$

$$=R_{w_1 w_2}(\xi)+\int_0^{\infty} h(s)(E\{w_1(n)w_1(n+\xi-s)\}+E\{w_1(n)(v(n)/\omega_s(n))(n+\xi-s)\})ds$$

$$=R_{w_1 w_2}(\xi)+\int_0^{\infty} h(s)(R_{ww_1}(\xi-s)+R_{w_1 f_s}(\xi-s))ds \qquad (2)$$

Based on assumption of independence of both the noise w_2(n) and the production signal f(n) on the auxiliary measurement signal w_1(n) ,the cross-correlation function $R_{w_1 w_2}(\xi)$ and $R_{w_1 f}(\xi)$ are equal to zero and finally obtain

$$R_{w_1 p}(\xi)=\int_0^{\infty} h(s)R_{w_1 w_1}(\xi-s)ds \qquad (3)$$

If eqn.(3) is transformed into frequency domain ,the frequency response of the system can be determined as

$$G_1(\omega)=\frac{S_{w_1 p}(\omega)}{S_{w_1 w_1}(\omega)}$$

Which is given by the ratio of the cross and power spectrum and can be obtained by Fourier transform of the measured correlation function.

Following the same procedure to get the transfer function between w_1 and v,

$$G_2=\frac{S_{w_1 v}(\omega)}{S_{w_1 w_1}(\omega)}$$

If assume v (n) =f (n) +w_1 (n) as the voltage change of the induction motor input. Hence the real power model of the induction motor by changing voltage/ supply frequency is

$$G=\frac{\Delta p}{\Delta v}=\frac{G_1}{G_2}=\frac{S_{w_1 p}(\omega)}{S_{w_1 v}(\omega)}$$

Similarly, reactive power model of induction motor by changing voltage/supply frequency is,

$$G=\frac{\Delta q}{\Delta v}=\frac{G_1}{G_2}=\frac{S_{w_1 q}(\omega)}{S_{w_1 v}(\omega)}$$

3. THEORY FOR IDENTIFICATION OF A SYSTEM UNDER FEEDBACK WITH MULTIPLE NOISE

The block diagram of the interaction between power system and load is shown in fig.2.W1 is the white noise of the power system and W2 is the white noise of load . These two indicates disturbance of the power system and load. The symbol X is the voltage or frequency/angle changes in power system and Y is the real or reactive power of the load.

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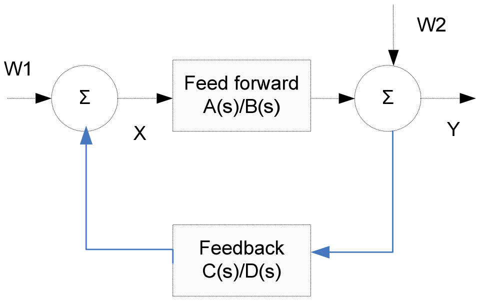

Figure2.Identification when there are multiple disturbances and feedback

The more general case as in figure 2 can refer to cases where the power system affects the load and the load affects the power measurement. When the load is significant for the power system strength then the feedback structures becomes important.

In fig.1 if W2=0 then the transfer function between X and Y would identify the feed forward system. If W1=0 then the transfer function between Y and X would identify the feedback system. When both terms are present there is no clear separation between the effects.

The idea behind this processing is to find the best predictor for X and Y. The white noise component as the residuals for X and Y will thus be the white noise inputs W1 and W2.Thus the process can be to find the transfer function from W1 to both X and Y and the ratio will give the feed forward system A(s)/B(s) ,provided W1 and W2 are uncorrelated. Similarly we can find the transfer function from W2 to Y and to X and the ratio will give the feedback system C(s)/D(s).

4. SIMULATION

A a key component of load modelling a method has been developed to identify the induction motor model which was simulated in MATLAB. Here the induction motor is examined with two different types of shaft load.,

4.1 INDUCTION MOTOR WITH LINEAR LOAD

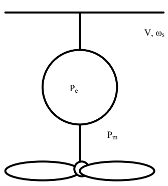

Figure 3.Induction motor with fan load

An induction motor with a linear load is simulated in MATLAB by using first order swing equation (ignoring the electrical transient) the equation is,

$$\frac{d\omega_r}{dt} = \frac{P_e - P_m}{2H}$$

Where, P_e is electrical power of induction motor and P_m is mechanical power of the load, H inertia and ω_r angular speed of the rotor. The load bus input is V and the supply frequency ω_s .To find out the model of the induction motor , consider voltage (V) and angular frequency (ω_s) of supply change as unpredictable random process with mean 1 and variance 0.001. The mean and variance are constant so the system is a stationary random process in wide sense. The least square method is used to extract noise w_1 and w_2 from input data and output data. To compare the simulated result to the real system, the algebraic equation of the induction motor is generated.

The linear time invariant transfer function of the induction motor by changing the voltage is,

$$\frac{\Delta Pe}{\Delta V} = \frac{2V_0 Sl_0}{Rr} \frac{s + \frac{B}{2H} + \frac{V_0^2}{2\omega_s HR_r} - \frac{V_0^3}{2\omega_s^2 HR_r}}{s + \frac{B}{2H} + \frac{V_0^2}{2HR_r\omega_s}}$$

Where,

V_0, S_{l_0} is the steady state voltage and slip of an induction motor. B is mechanical torque coefficient. H inertia of the rotor, Rr rotor resistance.

By using a sampling interval of 0.04 and time duration 200sec, The identified transfer function of the induction motor is shown in fig.4

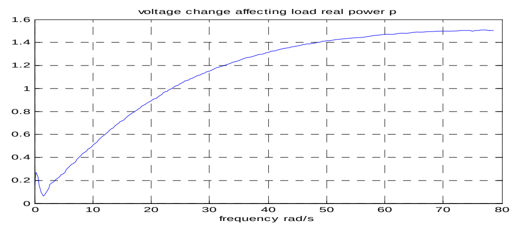

Figure 4a.magnitude of estimated transfer function $\frac{\Delta Pe}{\Delta V}$

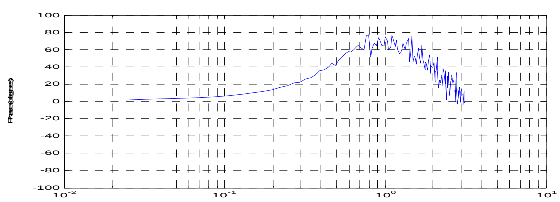

Figure 4a.Phase of estimated transfer function $\frac{\Delta Pe}{\Delta V}$

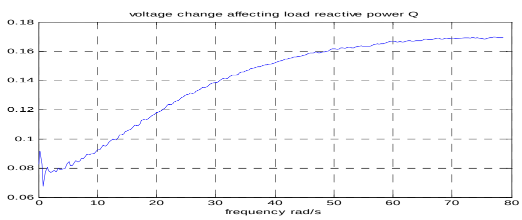

Figure 5a.Magnitude of estimated transfer function $\frac{\Delta Qe}{\Delta V}$

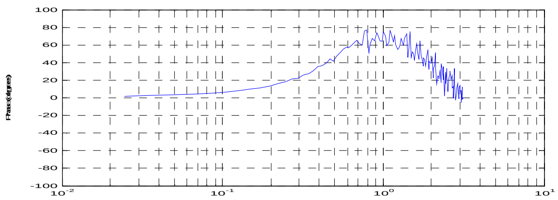

Figure 5b.Phase of estimated transfer function $\frac{\Delta Qe}{\Delta V}$

The transfer function found from the linearized model is shown in fig.6 and fig.7

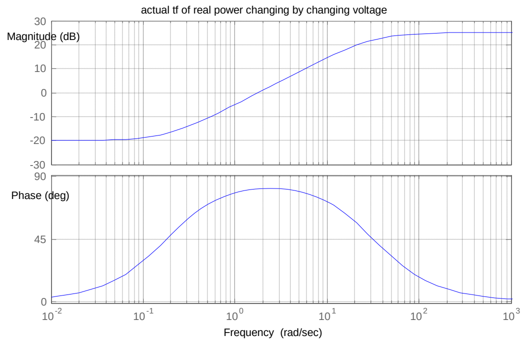

Figure 6.Algebraic transfer function $\frac{\Delta Pe}{\Delta V}$

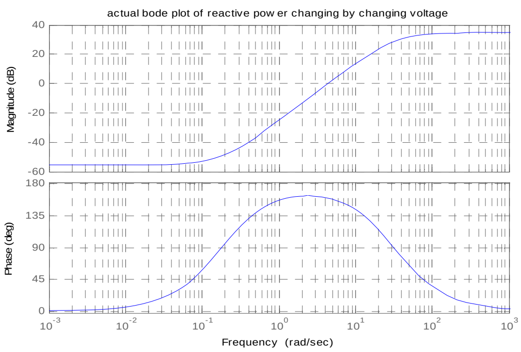

Figure 7. Algebraic transfer function $\frac{\Delta Qe}{\Delta V}$

Similarly, the linear time invariant transfer function of the induction motor by changing the supply frequency is,

$$\frac{\Delta Pe}{\Delta f}=\frac{V^2}{RrW_s}\frac{s+\frac{B}{2H}}{s+\frac{B}{2H}+\frac{V_0^2}{2HR_r\omega_s}}$$

$$\frac{\Delta Qe}{\Delta f}=\frac{V_0{}^2X}{Rr^2\omega_s{}^2}\frac{(s+\frac{B}{2H})^2}{(s+\frac{B}{2H}+\frac{V_0^2}{2HR_r\omega_s})^2}$$

Where V bus voltage and X induction motor reactance.

The estimated real and reactive transfer function by changing supply frequency are shown in fig.7 and fig.8

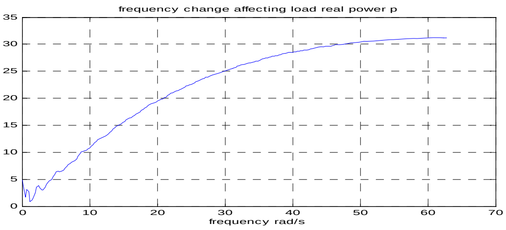

Figure 7a.estimated transfer function $\frac{\Delta Pe}{\Delta f}$

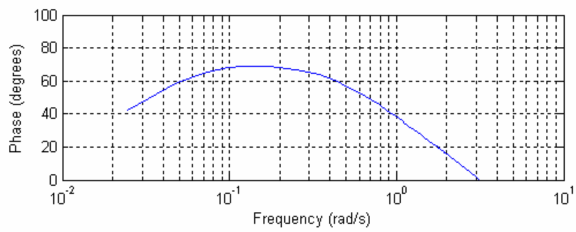

Figure 7b.estimated transfer function $\frac{\Delta Pe}{\Delta f}$

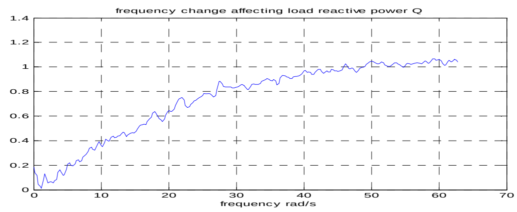

Figure 8a.Estimated transfer function $\frac{\Delta Qe}{\Delta f}$

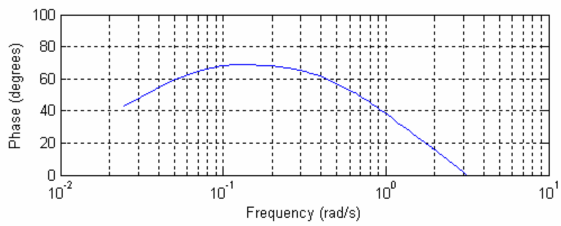

Figure 8b.Estimated transfer function $\frac{\Delta Qe}{\Delta f}$

The actual real and reactive power transfer function by changing supply frequency are shown in fig.9 and 10

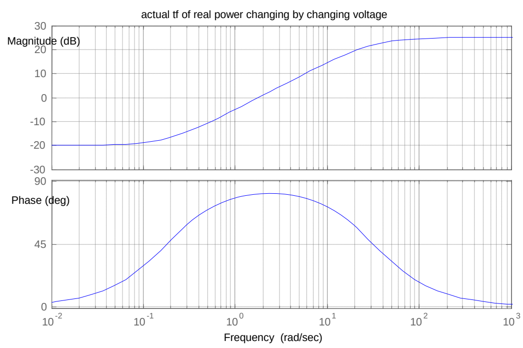

Figure 9.Algebraic transfer function $\frac{\Delta Pe}{\Delta f}$

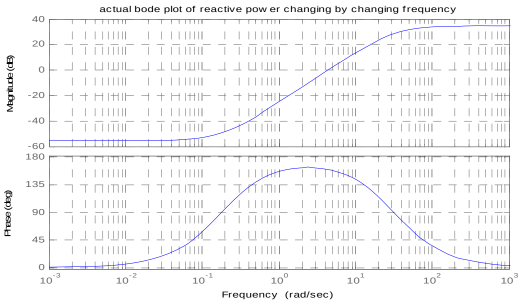

Figure 10.Algebraic transfer function $\frac{\Delta Qe}{\Delta f}$

4.2 INDUCTION MOTOR WITH SPRINGY SHAFT LOAD

Similarly induction motor with springy shaft fan load simulated by swing equation,

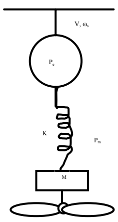

Figure 11.Induction motor with springy shaft fan load

By using a sampling period of 0.025sec and time duration 250sec, the identified transfer function of the induction motor with springy shaft load is shown in fig.12, fig.13 d fig.14 and fig.15 also actual transfer function is shown in fig.16, fig.17, fig18 and fig.19.

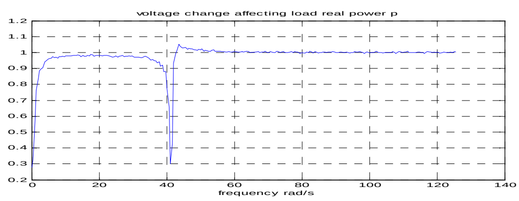

Figure 12a.Magnitude of estimated transfer function $\frac{\Delta Pe}{\Delta v}$

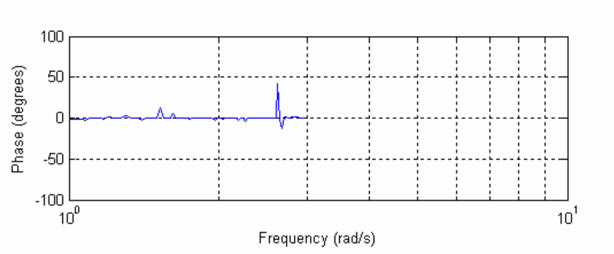

Figure 12b.Phase of estimated transfer function $\frac{\Delta Pe}{\Delta v}$

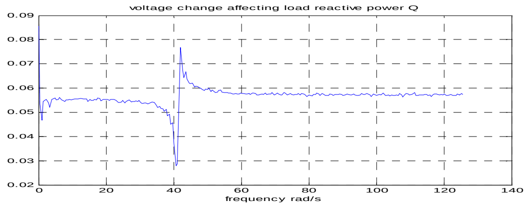

Figure13a.Magnitudeof estimated transfer function $\frac{\Delta Qe}{\Delta v}$

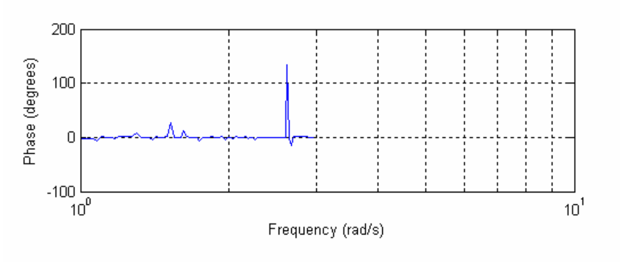

Figure 13b.Phase of estimated transfer function $\frac{\Delta Qe}{\Delta v}$

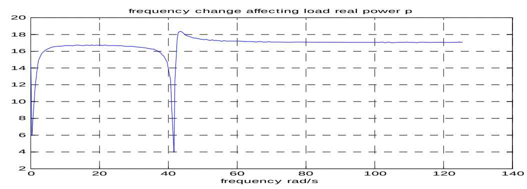

Figure 14a.Magnitude of estimated transfer function $\frac{\Delta Pe}{\Delta f}$

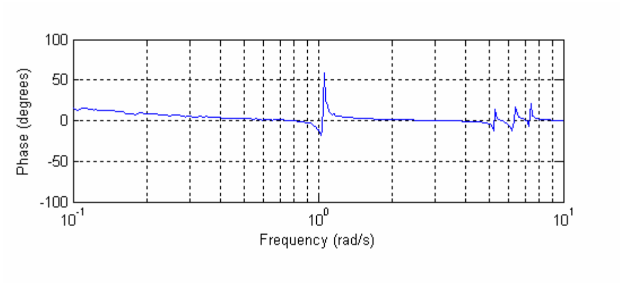

Figure 14b.Phase of estimated transfer function $\frac{\Delta Pe}{\Delta f}$

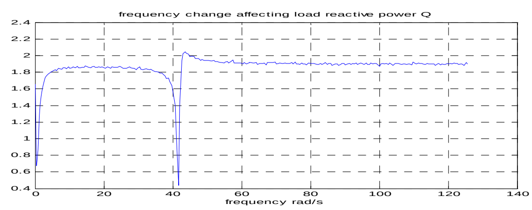

Figure 15a.Magnitudeof estimated transfer function $\frac{\Delta Qe}{\Delta f}$

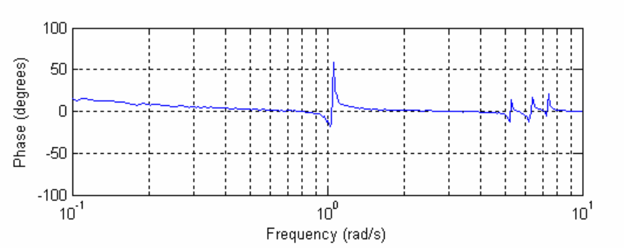

Figure 15b.Phase of estimated transfer function $\frac{\Delta Qe}{\Delta f}$

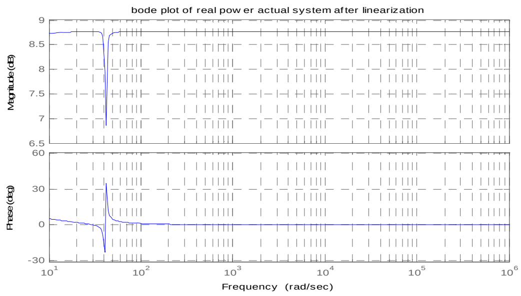

Figure 16.Actual transfer function $\frac{\Delta Pe}{\Delta v}$

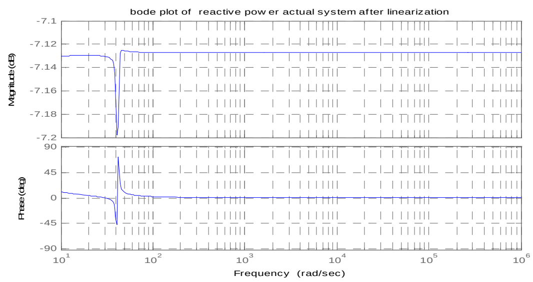

Figure 17.Actual transfer function $\frac{\Delta Qe}{\Delta v}$

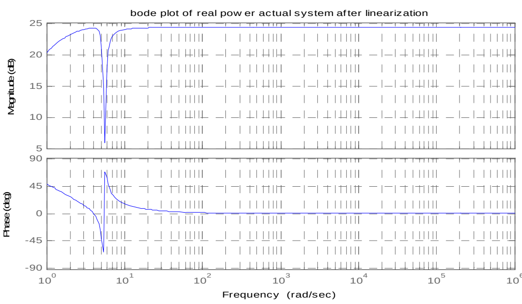

Figure 18.Actual transfer function $\frac{\Delta Pe}{\Delta f}$

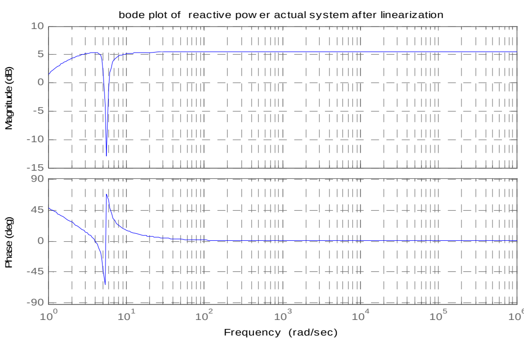

Figure 19.Actual transfer function $\frac{\Delta Qe}{\Delta f}$

5. CONFIRM THE THEORY BY USING REAL DATA

To identify the load model with multiple noises, QUT has installed a phase measurement device in south pine substation to record system quantities such as bus voltage, feeder current and phase angle. On basis of these data, frequency, real and reactive power's data have been obtained.

5.1 Frequency f –load P model:

The load model based on frequency f and load P is created as shown in fig.1.w1 is the residual of f and w2 is the residual of load P. Based on this model transfer function A(s)/B(s) shows the frequency f changes affecting load P while Transfer function C(s)/D(s) shows load P changes affecting frequency f. The spectrum of the transfer functions are shown in fig.20 & 21

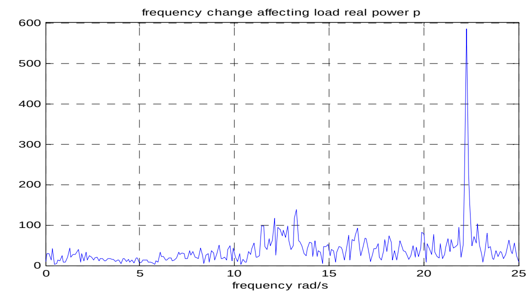

Figure 20.frequency changes affect Load P

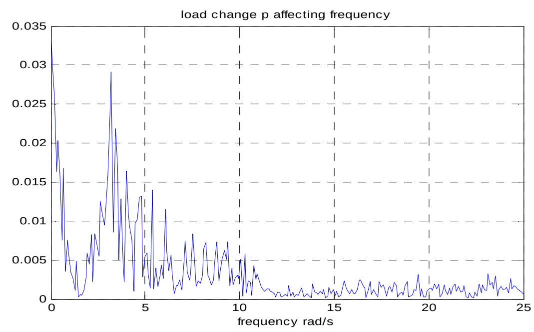

Figure 21.Load P changes affecting frequency

5.2 Voltage V –load P model:

Similarly load model for voltage changes to load changes and vice- versa are shown in fig.22 & fig.23

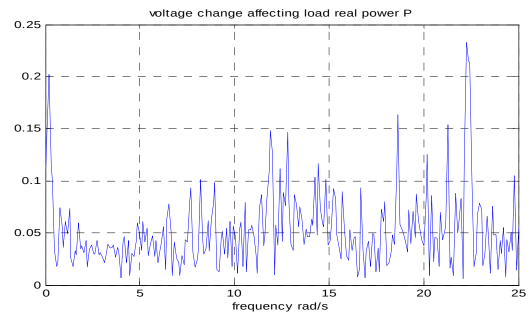

Figure 22.Voltage changes affects load P

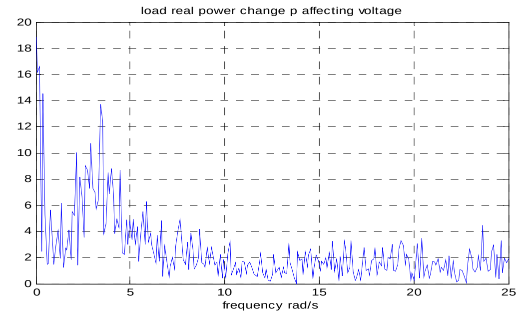

Figure 23.Load changes affect Voltage V.

5.3 Voltage V-reactive power Q model:

Bus voltage changes to reactive power changes and vice versa are shown in fig.24 & 25

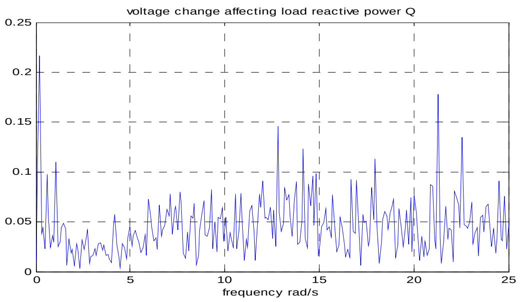

Figure 24. Voltage changes affect Load Q.

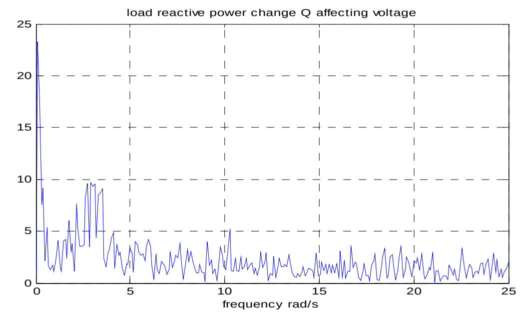

Figure 25.Load Q changes affect Voltage changes.

5.4 **Frequency f-Load Q model:**

Following the same way to obtain load model of frequency changes to load reactive power changes and vice versa are shown in fig.26 & 27

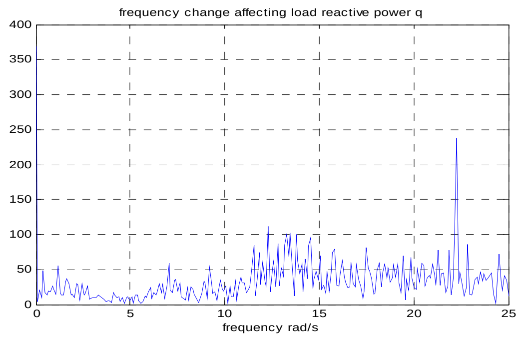

Figure 26.frequency changes affect Load Q changes

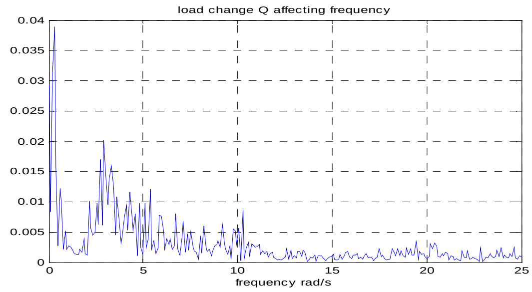

Figure 27.Load changes Q affect frequency changes.

5.5 Spectrum explanation:

Composite loads are the main form we see in a power system. But the only frequency dependant loads we expect are motors, especially induction motors, which has great use in industries. So frequency f to load P and Q model need to be explained in terms of the induction motor characteristic. We can't explain fig.20 from fig.9 or fig.18 We only can explain that there are composite induction motors working so based on fig.9 or fig.18 we can't explain the real/Reactive power changes to frequency. We need to do further research to explain the real data changes with frequency.

Voltage changes , changes real and reactive power of composite load of a power system. Which is explained in fig.22 and fig.24.We know that composite load consist of static and dynamic load, as a static load there might be pure resistive and resistive-passive load. When voltage is changing with low frequency pure resistive load power is constant but passive load power is increased at low frequency of voltage change and decreased with high frequency change of voltage.

From fig.21 and fig.27 we can explain load real/reactive power changes affects power system frequency and from fig.23 and fig.25 can explain load real/reactive power changes ,power system voltage. Load real and reactive power changes power system voltage and frequency at low frequency but it can't affect the power system parameters at mid to high frequency. So if we change load at high frequency it doesn't affect power system parameters but in low frequency it affects the parameters significantly.

DISCUSSION

The Cross-correlation identification which has been developed in this paper is theoretically exact. The model has been considered that there are no relation between w_1, w2 and f(t),w_1.But actually ,the relationship are not totally zero. So we can only suppose that their value is small enough in comparison with the desire component that their influence will be negligible. Also signal sequence length is important for precision correlation analysis. So it is important to choose reasonably good length signal. In this problem the signal length is 10000.for getting the better estimate of Rw_1p,divide the 10000 signal sequence into 8 window, averaging them into 512 samples. The cross –correlation identification is applicable for discrete modeling of continuous time system when the upper limit of their working frequency band is lower than the nyquist frequency of the sampling has been used. Therefore, sampling rate is important to achieve satisfactory result. We used MATLAB function Tfestimate to implement cross-correlation identification. .But it is impossible to find out phase characteristic so we used MATLAB Spa function to identify phase characteristic. Actually tfestimate based on periodogram for that reason we couldn't find out phase characteristic.

It is found that the estimation of system under feedback with multiple noise sources can give erroneous answer if the structure of the system is not carefully observed. This report shows one method of processing the data such that the separate components of the model can be extracted. the process was shown to yield reasonable results for the two components of relationship of system on load and the load on the system for the particular case of the south pine load. There is still a fundamental limit that for frequencies where the signal level are poor, the quality of estimation reduces.

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