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Decomposition of aggregated load: Finding Induction motor fraction in real load

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***Abstract*-** The aim of this paper is to show how to seperate models of the different motor load and static load components from measurements at a system bus. The Induction motor is considered as the main dynamic load and in the practise for major transmission busses there will be many and various induction motors contributing. Particularly at an industrial bus most of the load is dynamic type but in the commercial and the residential case, the static load percentage is higher than the dynamic load. Rather than trying to extract models of many machines this paper seeks to identify groups of induction motors to represent the dynamic load. In this paper there are three groups of induction motor used to characterize the load. These are the small group (4kw to 11kw), medium group (15kw to 180kw) and large group (above 630kw). The paper examines loads with different percentage contribution of each machine and simulates the composite model in Matlab. From composited model, to the paer determines motor group percentage contribution by using least square algorithms. To implement this theory to other bus types such as residential and commercials it is good to represent that total as a combination of the three composite motor load groups, constant impedance load and constant power load. To validate the theory, 24hrs of Sydney West data is de-composed according into the three groups of motor model and the results discussed.

Introduction

For power system analysis, load modeling is very important [1, 2]. In particular Load modelling is used for grid planning and operation [3]. Accurate load modelling is important to correctly predict the resoponce of the system to disturbances. With a poor load model we would need to operate the system with a higher safety margin Ref.[6] demonstrated the need for accurate modelling of load. But accurate load modelling is continuously a difficult task due to several factors such as [1], a. large number of diverse load components b. Ownership and Location of load devices in customer facilities is not directly accessible to the electric utilities c. Changing load composition with time of day and week, seasons, weather and through time d. Lack of precise inform on the composition of the load e. Uncertainties regarding the characteristics of many load components, particularly for large frequency or voltage variations.

Loads are very variable in nature. So it is necessary to consider the dynamic behaviors of loads [4]. Motors consume 60-70% of energy from the power system; therefore, the dynamic characteristics of motors are critical for dynamic load modeling [4]. In most cases induction motors reduce system stability. [5] Load at a given bus may include many types of induction motor, each having different dynamic characteristic and each operating at a different steady state condition[6] and static load as well. In Ref.[7] it is shown that one single motor is not a right choice for simulating the bus bar dynamic load. Many paper have been published about aggregate or composite load modeling[6-14].these paper are considered the composite load as a combination of static and dynamic load model. Ref.[13] considered the static load as a combination of constant impedance load and constant power load and as a dynamic load an induction motor is considered respectively. Ref.[12] used ZIP model for static load and an induction motor for dynamic load. Ref.[14] proposed a composite model which consists of 80% static load and 20% dynamic load. In this paper a load with ten-composited induction motors, a constant impedance and a constant power load are used for a decomposition example.

I. THEORY

A. Theory for Aggregation/Composition

Many papers have been published about the aggregation of induction motors and the representation of a group of motors as a single motor to facilitate the computational process. In this Ref.[6] aggregation is not being done for representing groups of induction machine as a single machine rather it is done to represent explicitly the real power system load as accurately as we can consistent with the quality of the identification. In this paper, two methods of aggregation are described. One is method A which used weighted average of the respective parameter and method B is almost similar to method A but for calculating electric parameters it uses the weighted average of admittance rather than impedance. The outcomes of all the techniques are approximate in nature [6]. In this work, method A is being used to composite 10 induction motors shown in fig.1.

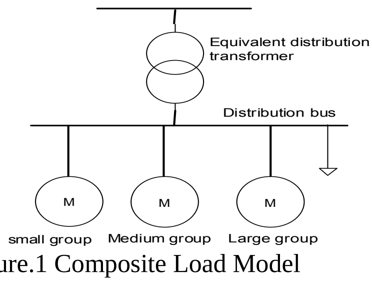

Figure.1 Composite Load Model

The total power of composited 10 motors is,

$$P_{agg} = \sum_{i=1}^{10} \alpha_i P_i \quad (1)$$

Where P_i =individual motor power and $\alpha_i = \frac{n_i P_i}{P_{agg}}$ =Percentage contribution of each machine, where n_i =no of motors=10.

B. Theory for decomposition

Least square identification is being used to decompose the measured composite motor response. The least square equation is,

$$X\theta = Y \quad (2)$$

Here Y =the real magnitude of aggregated real power to frequency change transfer function

θ =Percentage contribution of each motor,

And X =the real magnitude of individual motor real power to frequency change transfer function

Therefore if Y and X data are available it is easy to calculate the percentage contribution of each motor.

Usually power system variation affects the load and load variation affects the power system. Therefore, to compare the real system with simulated system, the simulation environment is divided into four sections. The four sections are described below,

B1. Open loop

In this case it is considered that the power system affects the load only. For finding out the time domain real and reactive input power of the induction motor, it is simulated in MATLAB code "ode45". The 5^{th} order induction motor model over a time duration of 20sec that is described step by step in Ref.[15] is used here. The step by step procedure to perform composition and decomposition using least square method in MATLAB are as follows,

1. In order to identify the different percentage motor from composite induction motor response, firstly choose the percentage contribution of each motor. Then add up time domain real power of each motor by using equation (1) to find out composited power of the 10 motors in time domain.

2. Secondly, calculate the frequency domain transfer function of individual motor and composited motor of small change of system frequency. MATLAB function TFESTIMATE is used to find out the transfer function.

3. Substitute the transfer function real magnitude value of individual motor and composite motor in the equation (2) to find out the percentage contribution of each motor.

B2. Feedback system

Load dynamics can be thought of as feedback mechanisms, which influence system behaviours. To understand how load is affecting the system, a closed loop model is developed and implemented to decompose the load. In steps 1-4 for the open loop process, the natural variation of system frequency is considered. To calculate the closed loop system, the closed loop transfer function is incorporated with the open loop transfer function. Implementing that theory as well as following steps 1-3 to do composition and de-composition for closed loop system are similar to the open loop.

B3. Feedback with constant impedance load and constant power load

One example of a total aggregated power when constant impedance and constant power load are included is,

$$P_{agg} = \sum_{1}^{10} \alpha_i P_i + \frac{V^2}{20} + 2100 \quad (3)$$

To represent the load at any bus, constant impedance load and constant power load are incorporated with composite motor load. For composition and decomposition steps 1-3 are followed. Constant impedance load and constant power load not affects the composite motor frequency to real power output .Constant impedance load is depended on voltage and constant power load is not depended on either frequency or voltage. The voltage is assumed constant at this stage. Therefore, the composite transfer function of frequency change to real power change is same as feedback transfer function. The percentage contribution of each machine is same. This can be understood from simulation result in simulation section.

B4 Feedback with constant impedance load, constant power load with variable voltage and frequency

Changing the frequency means slip is changing in the induction motor, that in turn changes the voltage at the system bus [16]. Therefore if small change of frequency is considered in the system, small change of voltage should be considered as well. The closed loop system is simulated again for composite motor with constant impedance and constant power load. In this case system frequency and voltage both are changing simultaneously. The composite motor transfer function of the frequency to the real power change affects due to the voltage perturbation and that in return change the percentage contribution of each motor.

The simulation section shows the step-by-step process sequentially.

C. Proposed idea for decomposition of the real data

The real data is collected from Sydney West substation Phasor measurement unit. In that substation, the load consists of constant impedance load, constant power load and also dynamics load. It is assumed that the frequency change affects the composite induction motor load only.

There is no information available to understand whether it is residential/commercial induction load or industrial/agricultural induction load. Usually large motors are used in industry and small power rating motors are used in residential premises. In this circumstance if it is possible to decompose the composite induction motor load then it may be possible to tell whether it is residential or industrial load according to the power rating. But there is normally no information about the type of motor that is involved in the composite induction motor load or the percentage contribution of the type of load is composited in composite motor.

In previous section, how to decompose the composite motor if the individual motor transfer function real magnitude data is available is described. Since, knowledge about the individual motor is necessary. Hence following steps are adopted to decompose the real data,

1. Select one motor from each group and determine its transfer function according to equation (1) and name it as a template composite motor model.

2. Put the small, medium and large template motors real transfer function value to equation (2) as X and value of real data as Y. calculate the residue. If residue is not zero or small enough then check the frequency content of residue. If residue energy is quite high in low frequency band that means large motor template is not accurate. Thus need to change the motor parameter to fit it well. Decrease and increase the large/small/medium motor power in the composite template motor model and again follow the same procedure mentioned above to fit it with real data and calculate residue. If residue is really small then follow steps 3, otherwise if there is room for another motor then include another motor in the template composite motor and follow the same procedure to fit it with the real data. Sometimes the same motors just need to shift its inertia to provide a good fit with the data. Inertia changing of the motor means shifting the motor frequency peak in frequency domain.

3. The motor power ratings that exist in real data are already known.

4. Therefore, applying the least square theory to find out the percentage contribution of each motor.

In simulation section composition and decomposition are explained in detail with respect to real data.

II. Simulation Result

D1.10 motor composition without feedback (Open Loop)

Ten induction motors, power rating and parameters are mentioned in appendix. Those motor are simulated in MATLAB as an open loop-power system affects the load only. Natural frequency variation is considered and voltage is fixed. To make all the motor powers equal to 630kW, the contributions of the motors in composite motor are shown in tabular form below,

Power rating (kw)	11	15	4	7.5	18.5	22	30	45	180	630
Percentage	57	42	155	84	34	29	21	14	3	1

The time domain power is converted to frequency domain power. The real value of magnitude of transfer function is plotted in figure (2). The composite real magnitude and individual motor real magnitude are shown in figure (2) with different line style.

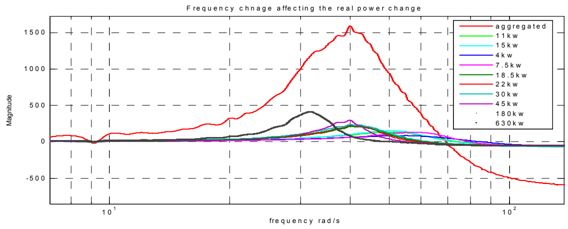

Figure.2 Transfer function of 10 motors and aggregated motors

Substitute the real magnitude value of composite one and individual motor one in equation (2) to find out the percentage contribution of each motor. In this case, only 10 rad/s to 100 rad/s frequency range of real magnitude value is considered. In this range, the magnitude value looks like simulated 5th order motor model.

In this case, the input is,

X_1=[Real (tfab (637:6370)) real (tfab2 (637:6370)) real (tfab3 (637:6370)) real (tfab4 (637:6370)) real (tfab5 (637:6370)) real (tfab6 (637:6370)) real (tfab7 (637:6370)) real (tfab8 (637:6370)) real (tfab9 (637:6370)) real (tfab10 (637:6370))];

Here, tfab is the real magnitude of the transfer function of motor 1 to 10

And the output is,

Y_1 =[Real (tfabagg (637:6370))];

Here, tfabagg is the aggregated real magnitude of the transfer function. The input and out values are put in equation (2) to get the percentage contribution.

The original and calculated percentage contribution of machine 1 to 10 is shown in figure (3),

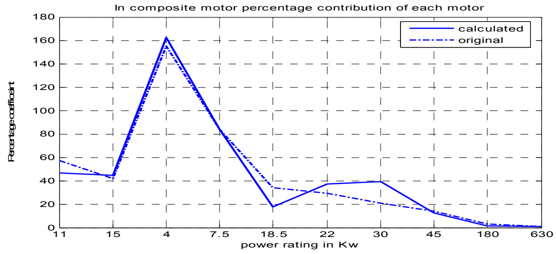

Figure.3 Original and estimated percentage contribution of 10 motors

15kw, 4kw, 7.5kw, 45kw, 180kw and 630kw percentage contribution of real and estimated one is exact but for 11kw, 4kw, 18.5kw, 22kw, 30kw percentage contribution estimation is not exact and error is around 20%.

D2.*10 motor composition with feedback*

Ten induction motors are simulated in MATLAB again with feed through-power system affecting the load and feed back that load changes is affecting the supply frequency. Governor is working like a low pass filter. Therefore, a low pass filter transfer function is inserted as a feedback transfer function with feed through and is simulated the whole system as a closed loop system. In the closed loop, the ten motors and composited motor feed through transfer function real magnitude value are showed in the figure (4).

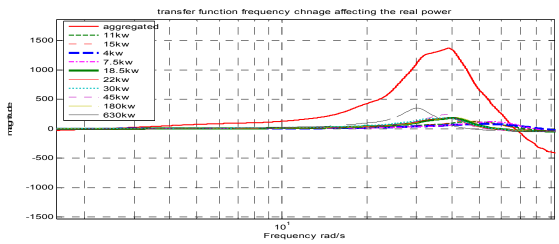

Figure.4 Transfer function of aggregated motor and 10 individual motors

In this case, the small motor, medium motor and large motor group are tried to fit into the composite motor and also tried to peel the percentage contribution of each group of motor.

Hence, the value of input is X_1 = [real (tfab4 (637:6370)) real (tfab22 (637:6370)) real (tfab630 (637:6370))];

And the value for output,

Y_2 = [Real (tfabagg (637:6370))];

Putting this value in equation (2), the percentage contribution of the groups of motor are tabulated below,

% Contribution	Smallgroup motor	Medium group motor	Largegroup motor
Estimate	303.5253	171.3685	0.8385
Actual	(57+155+84) =296	(42+34+29+21+14+3) =143	1

So, in this case, estimation is quite similar to actual data with 1.6% error for low group, 20% error with medium group and 23% error with large group.

D3. 10 motor composition with feedback and constant impedance and constant power load

Ten induction motors with closed loop system are simulated and composited with constant impedance type load and constant power type load. Constant impedance load power is proportional to square of voltage and voltage is constant here. Therefore, constant impedance power is constant in this case and this is added to composite motor load. The transfer function of the frequency change affecting real power of ten machines and aggregated machine are similar as figure (4)

Similarly, the small motor, the medium motor and the large motor group are fitted for the composite motor and computed the percentage contribution of each group motor.

Here, the value of input is X_1 = [real (tfab4 (637:6370)) real (tfab22 (637:6370)) real (tfab630 (637:6370))];

And the value for output,

Y_2 = [Real (tfabagg (637:6370))];

Put this value in equation (2), the percentage contribution of the groups of motor are tabulated below,

Thus, estimation is quite similar to actual data with 2.3% error with small group motor, 19% error with medium group motor and 16% error with large group motor.

D3. 10 motor composition with feedback and constant impedance, constant power load and also voltage perturbation:

Ten induction motors are simulated with closed loop system and composited with constant impedance type load and constant power type load. Constant impedance load power is proportional to square of voltage and voltage is not constant here. Therefore constant impedance power is variable in this case and this is added to composite motor load. The transfer function of the frequency change affects the real power of 10 machines and composited machine are shown in figure (5)

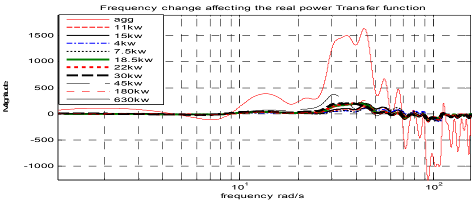

Figure.5 Transfer function of aggregated motor and 10 individual motors

In the similar way, the small motor, medium motor and large motor group are tried to fit into the composite motor and also tried to peel the percentage contribution of each group motor.

The value of input is X_1= [real (tfab4 (637:6370)) real (tfab22 (637:6370)) real (tfab630 (637:6370))];
And the value for output,
Y_2 = [Real (tfabagg (637:6370))];
Put this value in equation (2), the percentage contribution of the groups of motor are tabulated below,

% Contribution	Small group motor	Medium group motor	Large group motor
Estimate	324.5159	162.8380	0.8834
Actual	(57+155+84) =296	(42+34+29+21+14+3) =143	1

Since the estimation is quite similar to actual data with 9% error of small group motor, 13% error with medium group motor and 11% error with large group motor.

III. Real data

The transfer function of the frequency change to the real power change of Sydney West real data is developed in MATLAB and tried to decompose it based on the idea already proposed in section C.

At first, two motors from small and medium groups are tried to fit into this Real data in figure (6). But it seems there is still some room to fit another group of motor therefore third motor from large group of motor are tried to fit into the real data. After that, the real data is compared with the composite model of 15kW motor, 180kW motor and 630kW motor. To fit the composition one to the real one, the power of each motor is decreased. The inertia is another way of shifting of the 630kW and 15kW machine to right and left in frequency domain to match the composite real power to actual real power. It is shown in Figures (7-8)

the process is continued to fit the composite model to real data by changing the inertia and power of each motor. Whenever the composite one is matched with the real data, the three motor real magnitude value is selected as a template motor value and these three motor value can be used as input of the least square input X and the value of real data transfer function as an output Y. Substituting the value of X and Y in the equation (2) the percentage contribution of each machine (180kw, 15kw and 630kw) can be found in real data.

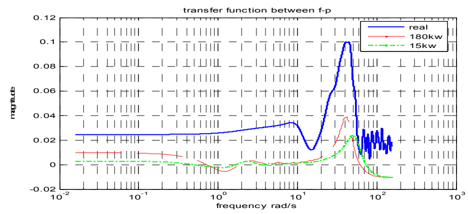

Figure.6 Transfer function

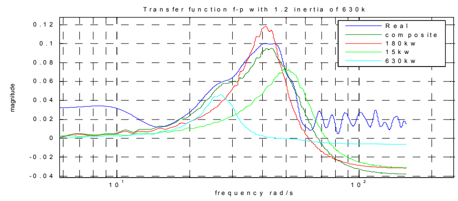

Figure.7 Transfer function

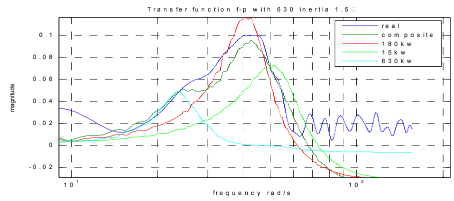

Figure.8 Transfer function

Same three template motor model data are used to find out composition in 24 hours Sydney west data. The percentage contributions of the each template motor in 24hrs with three different window data length of 30 min, 90 min and 120 min are shown in figures (9-11).

In 120 min data window length the variation of 15kW motor is quite substantial which means small type of appliances is switching on and off in 24hrs time but the large motor 630kW is turned on between 8am to 6pm and then it starts turning off. The large type motor is used in industry and it is to be expected that the big motor is turned on during daytime and turned off at the evening.

In 30 min window length the variation is quite large for all type of motor, which does not seem to match any real phenomenon, shown in figure (10)

In 90 min window length the variation is quite similar to 120 min window length. But the 15kW motor variation is different from 120 min window length shown in figure (9)

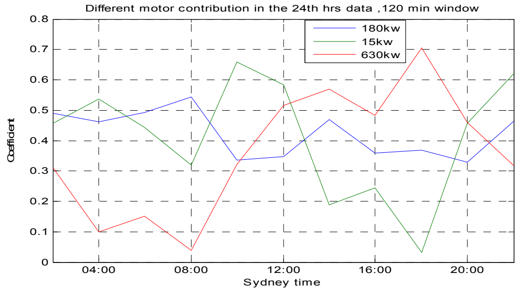

Figure.9 630kw, 15kw and 180kw motors percentage contribution in 24hrs a day

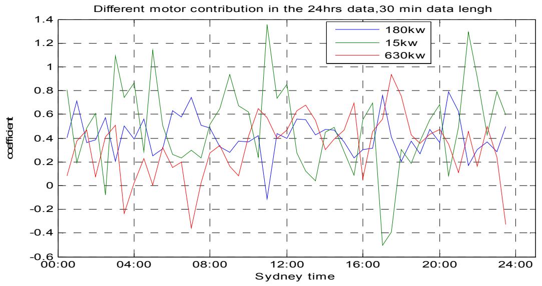

Figure.50 630kw, 15kw and 180kw motors percentage contribution in 24hrs a day

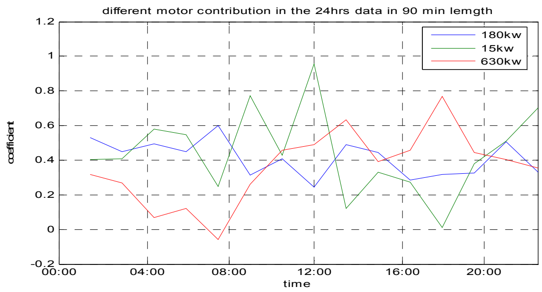

Figure.61 630kw, 15kw and 180kw motors Percentage contribution in 24hrs a day

IV. CONCLUSION

Hence the process of load model of identification from normal system variations in this paper offers promise of separation of motor load components from total load and the identification of the overall motor parameters.

The quality of identification is dependant on the degree of frequency variation visible in the system. When there are low levels of frequency variations in particular frequency bands then the quality of the load identification will be affected.

One potential limitation in this research work is that composite load is considered at a load bus and frequency and voltage small perturbation is at that same bus but in actual system load is not concentrated in a load bus rather than few buses in radial system. For small perturbation of frequency it doesn't really a matter for considering the composite load in a bus or in distributed bus but for large and small voltage perturbation it is a problem.

In this paper to analysis real data 120 min data length or 90 min data length gives the result that is quite similar to real world load changing phenomenon. Instead of real value of transfer function, complex value is used to calculate the percentage contribution and the similar result obtained. For this reason, the complex value magnitude of the transfer function was not considered.

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