COMPARISON OF AGGREGATION METHODS OF INDUCTION MOTOR MODELS FOR TRANSIENT STABILITY LOAD MODELING

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Abstract—This paper focusses on the comparison of the aggregation methods of multiple induction motors (IM) connected in parallel on the same bus into a single equivalent model using the no-load and locked-rotor and transformer method. The opearation for the former method is based on assumptions that in the no-load operating condition, the slips of all the IM are equal to zero while for the locked-rotor, the slips are unity. The latter method assumes that all the motors are represented by the transformer equivalent circuit model and thus the name transformer method. This study has been necessitated by the strong effects that the non-linear loads have on power system characteristics and therefore erroneous modeling of these devices continues to be an area of greater uncertainty.

Though various methods of aggregations have been used, comparison on their suitablity and accuracy has not been extensively explored. Appropriate dynamic load model aggregation reduces the computation time and provides a faster and efficient model derivation and parameters identification that are most sensitive to load dynamics. The simulations and analysis are carried out using Simulink. The performance is validated by evaluating the results obtained from individual and aggregate IM on IEEE 16 Bus standard system found in literature. The transient characteristics due to voltage disturbances of the aggregate IM and that of original IM group are simulated and compared to check the effectiveness of the aggrgation methods. The results shows that aggregation based on the formrer method is accurate than aggregation based on the latter method and can be used in modeling of large motors in any complex power system because of its high accuracy .

Key words: Aggregation methods, induction motor, voltage stability

1 INTRODUCTION

Different aggregation methods have been applied for induction motor load representation by several researchers [1]-[5] as a single equivalent model for ease and speed of power system analysis. However, comparison on the accuracy of these methods has not been meticulous.

The modeling of a group of induction motors is paramount in the dynamic analysis of induction motor (IM) since they contribute the biggest percentage of power system loads. This high percentage of induction motor loads in the power system causes delay during normal voltage recovery under fault conditions. It is however not practical to model every individual induction motors and especially large number of individual IM during the simulation studies and this can be highly time-consuming; therefore, aggregate models (single-unit equivalent models) is often employed. The accuracy of the results obtained with aggregate models depends in part on the assumptions made when deriving the aggregate motor and varies from method to method; grouping criterion is used to classify homogeneous motors [4]. Further, the accuracy of the results depends on how good the models are.

It is well known that load modeling on system dynamics is crucial; however it is still a big challenge. This complexity is brought about by the fact that load consists of various components with various characteristics, which nevertheless has to be represented as an equivalent single model. Further, it is the consumer of power who decides the order in which to connect their power consuming devices, thus making it even more intricate.

The goal of this paper is therefore to represent and compare methodology of aggregation of the nonlinear characteristic of induction motor loads from common bus bars namely; transformer-type equivalent and aggregation of a group of IM loads based on two special operating conditions i.e. no-load and locked rotor condition. These are achieved by Simulation of a group of induction motor model using a single equivalent motor model and analyze their suitability on parameter identification of aggregation load model. Matlab-based software is utilized in the simulations and analysis. The test results clearly demonstrates that, aggregation methods are of varying degrees of accuracy and are dependent on the assumptions made on derivation of the aggregate motor parameters. However, in this paper, the appropriateness of the aggregation methods is compared to identify the most suitable methods both under steady-state and under dynamic conditions of the power system. The efficiency of the aggregated and individual IM is estimated using the IEEE 16 bus standard system found in literature.

11 METHODOLOGY

A) THE AGGREGATION OF MULTIPLE INDUCTION MOTOR LOADS

Generally, large portion of power system loads are induction motors and their aggregation for parameter identifications and transient stability study is critical. The simulation of large group of IM takes time; therefore, in order to reduce the computation time, reduced order modeling is suggested to represent a group of motors with one or more aggregate motors. There are different aggregation methods proposed in the literature [1]-[5] and their accuracy depends on the assumptions made.

In this paper, an aggregation method based on no-load and locked-rotor [2] and transformer-type equivalent circuits [4] are compared.

Aggregation without making some assumptions can prove to be an intricate venture and therefore, in this paper the following assumptions were made:

All the motors are of the same type and are connected in parallel and at the same bus with no other load types.

The output power for each sizes of motor is maintained for ease of comparison under the two methods of aggregation of IM while the same number of poles is maintained.

Bus 3 of the 16 bus was selected for analysis of the system as detailed below:

$$\begin{gathered}\text{Total bus load=10Mw}\\ \text{Static load=8.32Mw}\\ \text{Dynamic load=(10-8.32)Mw=1.68Mw}\\ \text{1.68Mw=(1.68*^6/746)Hp=2250Hp}\end{gathered} \quad (1)$$

1) **TRANSFORMER-TYPE EQUIVALENT CIRCUIT MODEL**

The equations and development model used to obtain the aggregate motor model and their parameters can be found in [4].

In this paper k is taken as 0.98 and $\angle k = 0^\circ$ for the aggregate motor

$$z_O{}^{agg} = \frac{1}{\sum\limits_{i=1}^{N} \frac{1}{\left[Z_1 + Z_M\right]^i}}, \quad \textbf{(2)}$$

$$where Z_1 + Z_M = Z_O, Z_1 = R_1 + X_1, Z_M = R_C // X_M$$

$$Z_S{}^{agg} = \frac{1}{\sum\limits_{i=1}^{N} \frac{1}{Z_S{}^i}} where, Z_S = Z_2 + Z_3 \quad \textbf{(3)}$$

2) INDUCTION MOTOR AGGREGATION BASED ON NO-LOAD AND LOCKED-ROTOR TEST

This method is proposed by [6], where the parameters of the aggregate induction motor are determined from two operating conditions. However, the above method was first proposed by [7] and in this paper, the equivalent circuit parameters of the aggregation model are determined based on the same procedure. In the no-load operating conditions it is assumed that slips of all the induction motors are equal to zero while in the locked-rotor conditions the slips of all induction motors are equal to unity. The equations used to obtain the aggregate model can be found in [6] from (1)-(21) respectively.

Fig .1 shows the equivalent circuits of the aggregate induction motor load, where R_S-stator resistance, X_S-stator reactance, Rr-rotor resistance, Xr-rotor reactance, Xm-magnetizing reactance and S- Slip of the induction motor respectively whose parameters of the aggregated model are identified.

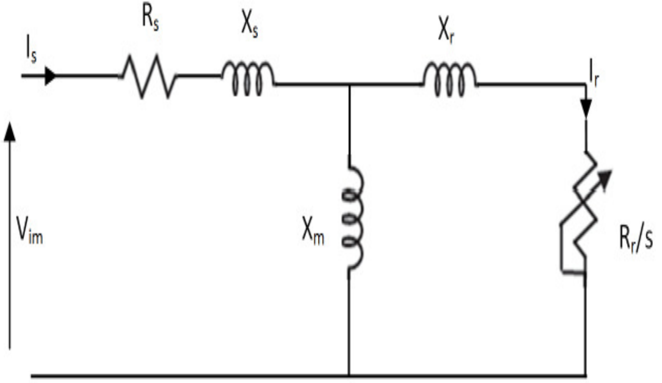

Fig. 1 Classical equivalent circuit model of an induction motor

111 GROUPING CRITERION

Generally, the above method is used to identify and group homogeneous motors. The inertia and open circuit time constant are often used to classify motors. In [7], the authors have developed a grouping criterion that may be expressed as:

$$G = a \times b \times H \quad \textbf{(4)}$$

$$a = \frac{X_m}{R_2} \quad \textbf{(5)}$$

$$b = \frac{(X1+X2)}{(R1+R2)} \quad \textbf{(6)}$$

The group is homogeneous if $1 \le \dfrac{Gmax}{G\min} \le 2.5$ **(7)**

Using the above grouping criterion, the different sizes of motors are classified into different groups. Aggregation based on this method is then done for different motor groups separately to find aggregate motors from each group.
Based on [7], below shows the typical load model parameters on individual small and large induction motors.

Table 1. Typical Parameters for individual small induction motors

HP	RS	Rr	XS	Xr	Xm	H	RPM
3	0.02	0.037	0.035	0.035	1.21	0.707	1760
25	0.022	0.047	0.05	0.05	1.95	0.528	1695
50	0.015	0.040	0.053	0.053	2.31	0.79	1750
100	0.011	0.047	0.053	0.053	2.51	1.06	1705

Table.2. Typical Parameters for individual large induction motors

HP	RS	Rr	XS	Xr	Xm	H
1000	0.0158	0.0104	0.0851	0.0851	7.63	0.711
500	0.0185	0.0132	0.0851	0.0851	3.81	0.527
250	0.0241	0.0141	0.0864	0.0864	3.03	0.659
500	0.0185	0.0132	0.0851	0.0851	3.81	0.527

1 Non Linear Model of Aggregated Power System

This model is used for analysis of large disturbance. The aggregated multi-machine power system can be represented by a set of first order nonlinear differential equations as in [9].

2 Linearized Model of Aggregated Power System

This model is used to analyze small signal stability of the power system. The signal of the multi-machine system in the matrix form is derived from the equations of the individual machines in the system after being linearized and combined to represent a multi-machine, multi-load system.

1V SIMULATION RESULTS

In this paper, an IEEE-16 bus standard network was used to compare the suitability and accuracy of aggregation methods in identification of motor parameters. The analysis demonstrates that aggregation of IM based on-load and locked-rotor condition yields comparatively better results of the aggregated motor parameters than the transformer-based method. This is illustrated in the appendix of table 3 to 4 which gives comparatively better results of the aggregate motor parameters compared to the typical and individual parameters based on the former aggregation method. The latter method gives some imprecise aggregated motor parameters that diverse from the typical motor parameters as in table 1 respectively.

Figures 2 to 5 demonstrate the effect of steady-state operation on aggregate and individual induction motors. The figures show a close resemblance between the aggregate and individual parameters thereby validating the results. Figures 6 to 9 illustrate the effect of transient fault on the aggregate and individual motor parameters. The fault was introduced at 0.25 secs and cleared at 0.3secs thereby resuming to normal operation. It can be seen that there are small discrepancies in time domain responses simulated from the model developed. The simulation results show a close similarity with minor variance. The graphs clearly draw a close similarity of the result obtained from the aggregation model to that obtained from the individual motors. However, these simulations show a close resemblance with the results found in [4], thereby validating the results. It is further seen in figure 8 that, under short circuit fault, the induction motors absorbs greater amount of reactive powers thereby demanding more current to maintain the load. This high reactive power demand by the load may cause the generator to lose its ability to act as a constant voltage source because of the field current limits. Under such scenario, the generator behaves like a constant voltage source behind the synchronous reactance and therefore its terminal voltage reduces and may cause the motor to stall.

Fig 2. Steady-state response of aggregate active & reactive power

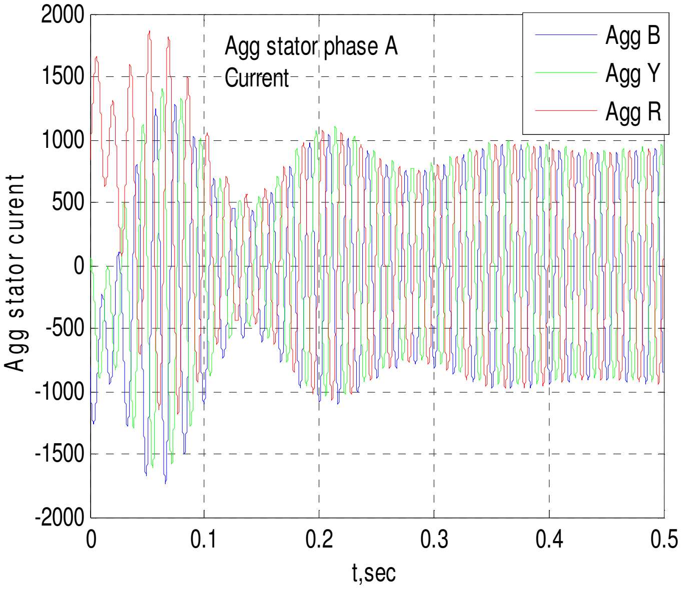

Fig 3. Steady-state response of aggregate stator phase A current

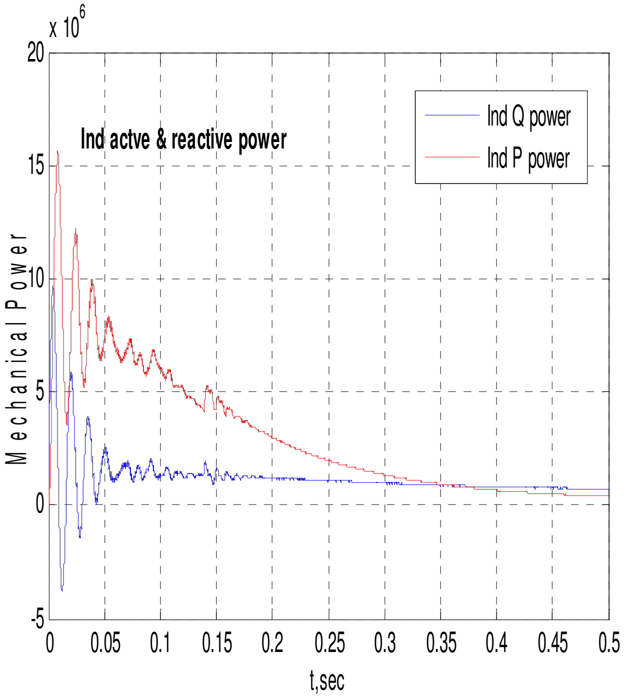

Fig 4. Steady-state response of individual active & reactive power

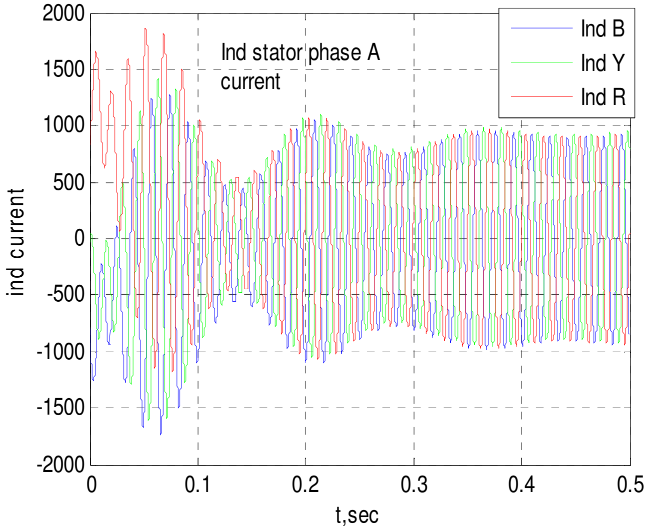

Fig 5. Steady_state responses of individual induction motors stator phase A current

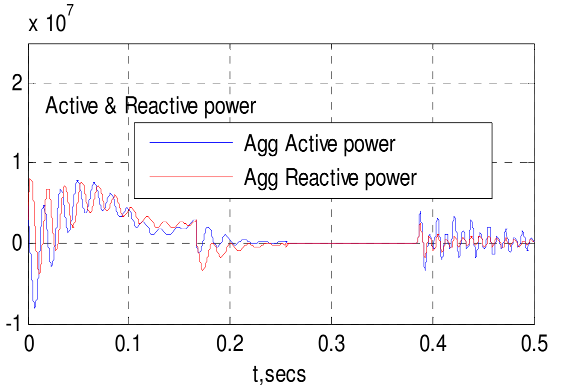

Fig 6. Switching transient responses of aggregate active & reactive power

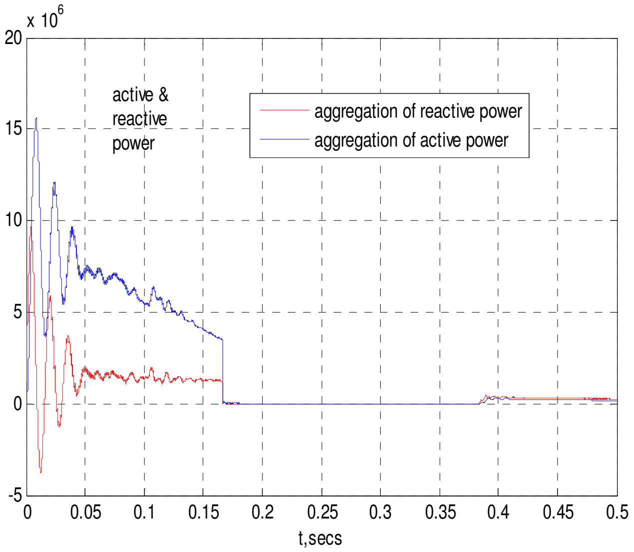

Fig 7. Switching transient responses of individual induction motors active & reactive power

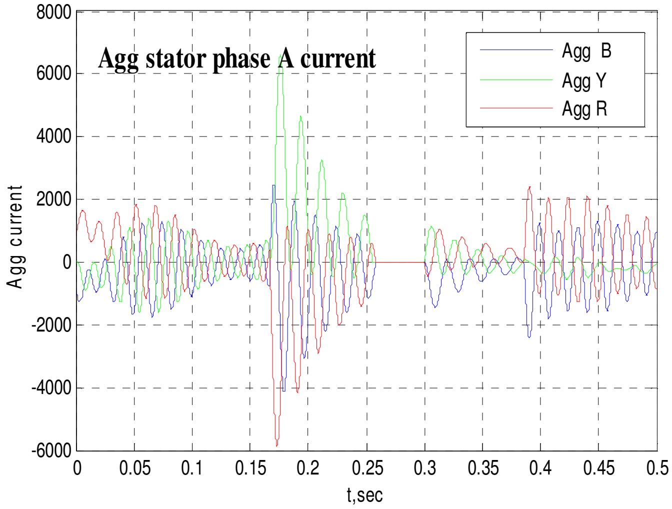

Fig 8. Switching transient responses of Aggregate induction motors stator phase A current

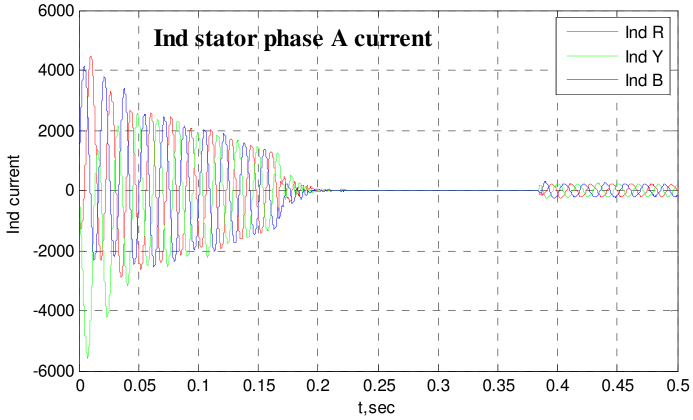

Fig 9. Switching transient responses of individual induction motors stator phase A current

V. CONCLUSION

It was found out that the transformer-type equivalent method of aggregation is less accurate in identification of the aggregated motor parameters as seen in tables 5 to 6 of the appendix. This method was compared to aggregation of multiple induction motors based on no-load and locked-rotor conditions which yielded better results that are comparable to individual motor parameters. This validated the latter method of aggregation employed.

The objective of this paper has been achieved. It has also been realized that unless a suitable method of aggregation is selected, the results is bound to generate some errors. The transient response of the aggregate and individual induction motors parameters draws a close similarity, thereby validating the method employed. It was also proved that method based on no-load and locked rotor conditions has good potential to be used in modeling of large motors in any complex power system because of its high accuracy. Therefore, for better analyses of power system, aggregation of IM is crucial for parameters identification and sensitivity to various power system dynamics under most of the operating conditions.

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Appendix

1) AGGREGATION BASED ON NO-LOAD AND LOCKED-ROTOR CONDITION

Table 3.Aggregated IM parameters of different sizes of an industrial consumer

P_{agg}	R_{1agg}	R_2agg	X_{1agg}	X_{2agg}	XM_{agg}
2250	0.02	0.04	0.03	0.03	1.21
2250	0.02	0.05	0.05	0.05	1.95
2250	0.02	0.04	0.05	0.05	2.31
2250	0.01	0.05	0.05	0.05	2.51

Table.4. Typical aggregated IM parameters

P_{agg}	R_{1agg}	R_2agg	X_{1agg}	X_{2agg}	XM_{agg}
2250	0.02	0.037	0.035	0.035	1.21
2250	0.022	0.047	0.050	0.050	1.95
2250	0.013	0.0402	0.0530	0.0530	2.31
2250	0.011	0.047	0.053	0.053	2.51

2) TRANSFORMER-TYPE EQUIVALENT CIRCUIT METHOD OF AGGREGATION

Table 5. Aggregated IM parameters of an industrial consumer

P_{agg}	R_{1agg}	R_2agg	X_{1agg}	X_{2agg}	XM_{agg}
2250	0.02	2	0.03	0.03	1.47
2250	0.02	2.5773	0.05	0.05	2.45
2250	0.02	4.253	0.05	0.05	2.45
2250	0.01	5.3191	0.05	0.05	2.451

Table 6. Typical induction motor parameters aggregation

P_{agg}	R_{1agg}	R_2agg	X_{1agg}	X_{2agg}	XM_{agg}
2250	0.02	1.85	0.035	0.035	1.715
2250	0.022	2.427	0.05	0.05	2.45
2250	0.0153	4.2766	0.053	0.053	2.597
2300	0.011	5	0.053	0.053	2.597